# DETERMINING WATER SUPPLY BENEFITS OF RESIDENTIAL RAINWATER HARVESTING IN INDIA USING TROPICAL RAINFALL MEASURING MISSION (TRMM) DATA

by

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## STATEMENT OF THESIS APPROVAL

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## ABSTRACT

The goal of this study was to analyze precipitation patterns in five different climatic regions across the country of India, to determine if rainwater harvesting (RWH) could provide sufficient indoor water for a typical household. Data were acquired from the United States National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) satellite for this study. For the study, six cities were selected in five different climatic regions based on the Koppen climate classification. Three-hour increment precipitation average intensities were extracted from TRMM_3B42 files for the centroid of each city. The analysis applied a water balance approach, with inflows estimated as runoff from the rooftop catchment and outflows estimated from water demand. Cistern sizes were varied from 757 to 18,927 liters and the catchment area was varied from 10 to 100 $m^3$ to quantify the performance of RWH across a range of system design conditions. As a result of the monsoonal climate in India, highly seasonal precipitation patterns occur. To study the seasonal precipitation influence, a dry-to-wet ratio was calculated as the average volume of precipitation for the months of June through August divided by the average volume of precipitation for the months of September through May. The Water Saving Efficiency (WSE) metric was calculated for each city on a yearly basis. The WSE values for each city were analyzed with the dry-to-wet ratios and precipitation volumes. The WSE varied from 2% to 6% for the smallest catchment area and cistern volume, to 20% to 50% for

the largest catchment area and cistern volume. Overall, the larger the area available and the larger the cistern, the higher the efficiency; however, for small catchment areas, the increases in cistern volume provided no additional benefit. A low dry-to-wet ratio resulted in a moderate efficiency if the precipitation volume was high, and a high dry-to-wet ratio resulted in a poor efficiency if the precipitation volume was low. Synthesizing the results, the general conclusion from this study is most cities in India will realize benefits from rainwater harvesting for urban water supply.

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## ACKNOWLEDGEMENTS

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# INTRODUCTION

India is in a water crisis. While 89% of the Indian population has *access* to improved water sources, access is generally very intermittent and availability to water is dropping across the nation (UNICEF, 2008). In the early 1980's, Bangalore had access to water 20 hrs/day and Chennai had access for 10-15 hrs/day; however, as of 2006 the availability of water has dropped to 2.5 hrs/day and 1.5 hrs/day, respectively (World Bank, 2006). The coping costs of lack of water is more expensive than municipal water itself, including walking for 2 hours a day to fetch water (World Bank, 2006). As stated by A. Shah:

> We need to recognize that self-provision of water is the best indicator of the failure of public water supply systems. Tubewells proliferate in canal commands because public irrigation managers are unable to deliver irrigation on demand. Urban households want their own boreholes because municipal service is inadequate and unreliable. (Shah and Patnaik, 2005)

The Falkenmark Indicator was established in 1989 and is likely the most widely used and accepted measure used to analyze the water stability in an area (Brown and Matlock, 2011). The index sets up four measures of water scarcity; namely no stress, stress, scarcity and absolute scarcity. The volume of water available defines the different levels of scarcity for each person, per year, in meters cubed. This volume includes the water indirectly used by a person for power generation, food preparation and industry, etc. The volumes of water and the categories are shown in Table 1. According to the United

Nations Food and Agriculture Organization (FAO), as cited in the Encyclopedia of Earth, India withdrew 627 $m^3$/yr per person in 2010, which according to Falkenmark's Indicator falls in the scarcity category, not far above the absolute scarcity level (The Encyclopedia of Earth, 2012).

To combat water scarcity in India, efforts are being made to harvest rainwater and (1) force it to infiltrate and recharge the depleted groundwater (Sakthivadivel, 2007) and (2) provide for direct water supply (Grover, 2010). Rainwater harvesting (RWH) systems can be simple or complex depending on the needs and available technology; there are a few components that are universal to all systems (Mechell, et al., 2009; Vita Nuova LLC, 2009). First a catchment area is needed, which is generally the roof of a building. Second, a method of collecting and transporting the water off the catchment is needed, generally a gutter/downspout system. Third, and optional, is screening or preliminary treatment. Fourth, a storage cistern needs to be provided. Finally, treatment is needed depending on the end use. Most commonly, filtration and disinfection are provided when indoor uses are in store for the captured rainwater (EPA, 2008; Mechell, et al., 2009). A pump may be provided to pressurize a downstream distribution system or to drive the water through a treatment unit. Figure 1 shows an image of a RWH system, which is also used to recharge groundwater.

A review of the literature reveals that RWH is widely researched and implemented in many parts of the world for various end uses. While RWH is of interest to many areas, the United States (US) is lacking on studies and involvement in this research. The literature review is divided up into three sections. The first section looks at a few studies to get a feel for the general overall opinion of RWH in the US. The second section takes a brief look at the attitudes towards RWH on a global scale. The third is a more in depth review of the studies performed in India pertaining to the subject at hand.

As one US based study points out, implementation of RWH has been slow and often overlooked in new development areas (Jensen, 2008), even though RWH has the potential to reduce indoor nonpotable water demand by 90% for municipal sources in areas with high annual precipitation volumes (>762 mm) and by 20-50% in areas with lower volumes of rain (Steffen, et al., 2013). Another US study found RWH could provide both community benefits (storm water control) and individual benefits (water cost savings) (Koenig, 2003).

The research on a global scale is much more comprehensive but covers a variety of topics. A study conducted in Germany analyzed if RWH could be used as a means to gain access to safe drinking water and defined potential issues that would arise (Helmreich and Horn, 2009). A Chinese study aimed to discover the causes of poverty in western China learned one of the root causes was water scarcity, and the most "easy-to-use water source with the highest potential" is RWH (Zhu, 2003). A study performed in the United Kingdom suggests RWH "feels right from a long-term sustainability perspective" (Way, 2010). Lastly a study performed in Japan, looked into potential health risks of RWH in Bangladesh and discovered significant microbial heath burdens leading to a recommended water safety plan (Kamir, 2010).

A fair amount of studies on RWH in India have been conducted for various end purposes, but the vast majority have been conducted to analyze the benefits of groundwater recharge (GWR). A study on the current water supply crisis in Chennai was investigated, and it was found that despite an abundance of annual precipitation (1300 mm), the area suffered from water supply shortages. Many of the government initiated resolutions were not effective, especially the pumping of groundwater aquifers. Yet RWH for GWR has had positive impacts on the subsurface level, including raising the water table, reducing urban flooding and controlling seawater intrusion (Jency, 2009). Another comprehensive study on sustainable urban water supply pointed out that Chennai is the first city to mandate RWH for new development; however, the mandate is solely for GWR. This practice provided no benefit to piped water supply, only to GWR (Srinivasan, 2010). A case study on the potential RWH benefits in urban India pointed out that 85% of the rural population and 55% of the urban population across the country use groundwater as the primary source for indoor water and points out that RWH is a "feasible, eco-friendly and beneficial" method for GWR (Sharma, 2009). A case study in Bangalore discovered groundwater use rates exceeded aquifer recharge rates and suggested RWH for GWR before the "city faces bleak water resource situation" (Suresh, 2001).

Meanwhile some studies have been conducted to see the potential benefit of RWH for water intended for indoor use. A survey driven study looked at the indoor water use activities and awareness of RWH technologies in the Hisar District of the Haryana state. The 763 surveyed household study found 77% of households are not satisfied with the duration of city supplied water and 86% of the households did not have an awareness of RWH technologies used for the acquisition of water (Singh and Turkiya, 2013). Another study found that despite India's rapid urbanization the security of the urban water supply was uncertain. It proceeded to discuss the many benefits of RWH and how the water could be used as secondary indoor water use, but RWH for indoor use is "left largely unexploited" (Grover A. R., 2010). The Chennai study mentioned above, points out that the term RWH, "refers to enhanced aquifer recharge; rather than collection of rainwater in cisterns for (indoor use)" (Srinivasan, 2010). While RWH has received significant attention across the planet (especially in India), the purpose of this technology, in India, has been almost exclusively for GWR. While this is a worthwhile effort, RWH to be used directly for indoor water use needs to receive more attention and become an everyday reality to the general public of India. Using RWH for indoor use alleviates the demand on groundwater resources.

The purpose of the present study is to provide a quantitative look into RWH's potential benefits to provide water for indoor use, for a "typical" household in six different climatic regions of India. For this paper, water for indoor use includes all of the following demands: drinking, toilet flushing, hand washing, bathing, food preparation, dish washing, washing clothes and watering plants. A Kossen climatic region classification map was consulted and six cities across India were chosen for analysis. The cities were chosen based upon varying climatic patterns (spatial variation) and being large urban centers (maximizing potential benefit to largest number of people). Various housing options for each city were analyzed and a typical living structure for a middle class Indian family was chosen. Satellite precipitation data was accessed for the center of each city and a set of surveys were distributed to typical Indian families to determine the daily indoor water use demand. A MATLAB script was written to perform a mass balance of the volume of water into a cistern (precipitation), and the volume of water out of the cistern (demand and spillage) on a daily basis. Water saving efficiency calculation was used on an annual basis and these values were compared to the average precipitation values and a ratio of dry months to wet months. The results provided both a spatial and temporal analysis of RWH potential for indoor water use in India.

Table 1: Falkenmark Indicator values for determining the water stability in a country

| Category | Volume (m3/year) |
|---|---|
| No Stress | >1700 |
| Stress | 1000-1700 |
| Scarcity | 500-1000 |
| Absolute Scarcity | <500 |

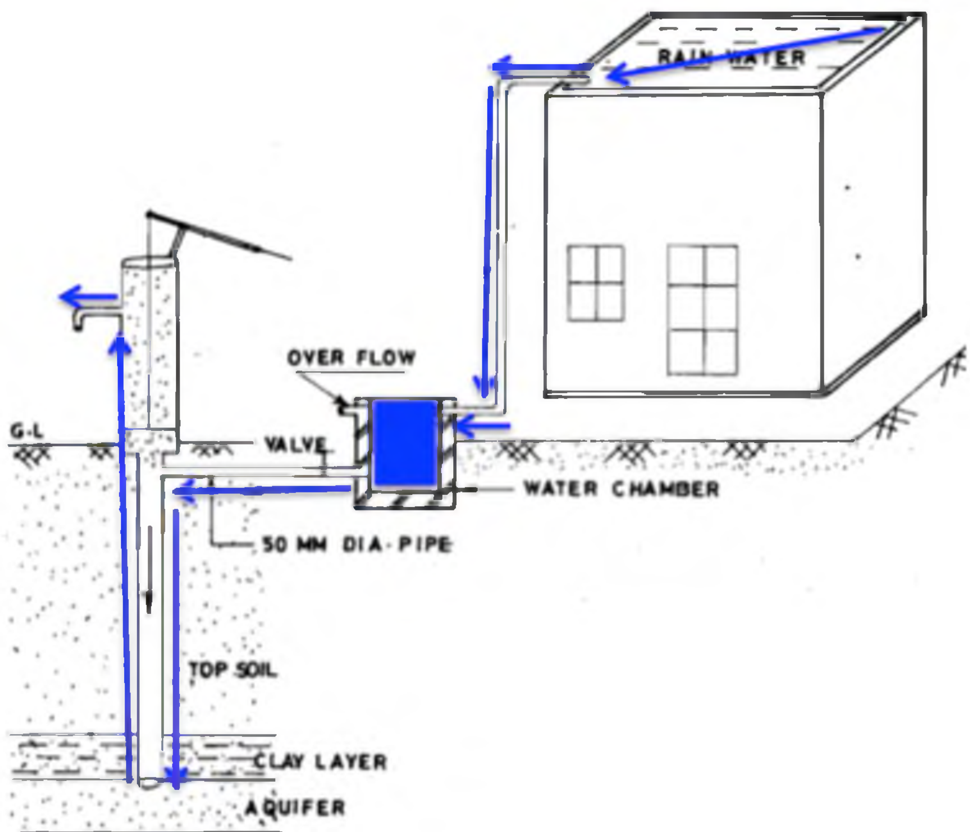


Figure 1: Simple RWH schematic showing path of water flow across catchment, conveyance, storage, recharge and withdrawal. Modified from Govt of India, 2002.

# METHODOLOGY

Six cities were chosen across India to provide a spatial analysis of several different precipitation patterns experienced in the different climatic regions. The cities were chosen based on varying geographic locations in the country, vast differences in population and varying climatic patterns. A climatic zone map of India using the Koppen classification system was consulted to analyze several different climatic patterns (Mapsof, 2012). Even with the vastly varying locations, there were many similarities in the types of housing. Each city analyzed has population of at least 4 million, minus the city in the Mountain Region given the sparse population centers in this region. Table 2 shows the cities, along with their approximate population (in millions of people) as of 2011 and their climatic region (Government of India, 2011). Figure 2 shows the locations of the six cities.

A common apartment housing style was chosen for this study. The apartment building is 4 stories tall and has approximately 8 apartments. This particular building was chosen based on an analysis of various housing options across the six analyzed cities using Google Earth images. A fellow civil engineer in India, Satish Kumar Vedulla, provided advice as to which types of housing are most common in urban settings for the majority of the population. See Figure 3.

One of the most important properties of any RWH building planning, is the catchment size (most often the roof size). For this study we are only considering the roof as the catchment, following the assumption that the buildings are often densely spaced. The area of the model building was calculated using Google Earth and GE Path (a freeware program used for calculating areas from Google Earth files). The building location was found in Google Earth, and a polygon was drawn on the roof, Figure 4. This polygon was saved as a KML file and imported into GE Path (Sgrillo, 2012). The area of the polygon was calculated as 167.2 $m^2$. Given the building houses 8 family units, the total apartment building catchment area was divided by 8, resulting with the "typical Indian household" catchment area being 21 $m^2$.

## Cistern Volume Methods

Several methods exist for determining the volume stored in a cistern. Most of these methods have been developed by engineers to determine the size needed for a reservoir storing large volumes of water. These same methods can be used for determining the volumes in a RWH storage cistern. The main methods that exist are (Jothiprakash and Sathe, 2009):

1. Ripple Diagram
2. Analytical Method
3. Sequent Peak Algorithm Method
4. Mass Balance Method

An analysis of a RWH system was conducted using these four methods. The results showed all of the methods calculated results within 0.90% of each other and once the volume was rounded to a reasonable cistern size, all four methods arrived at the same conclusion (Jothiprakash and Sathe, 2009). The method chosen for this analysis is the mass balance method.

## Mass Balance Method

The mass balance method is a simple water budget analysis method. The volume of the inflow water (roof runoff), demand and remaining water (storage) are analyzed for each time step (Panu and Rebneris, 1997). This is an iterative approach that requires changing the cistern size and rerunning the analysis allowing for analysis of multiple different cisterns. Optimal sizing involves storing enough water to meet the needed water demand, while minimizing the days of overflow and the days of the cistern being empty. Since most locations do not receive evenly distributed volumes of rainfall throughout the entire year, the RWH cistern ideally would be sufficiently large to store water during the wet season to meet the demands of the dry season.

To perform the mass balance method three pieces of information must be known for each time step: inflow volume, volume in cistern and household volume demand. Once this information is obtained, a mass balance calculation can determine the RWH unit volume to supplement centralized water demand and the volumes of spillage for each time step.

## Inflow Volume

The inflow volume is calculated using

$$Inflow = R_c * V_r * A * 1000^{-1} \quad \textbf{(1)}$$

where $\mathbf{R_c}$ is the runoff coefficient, $\mathbf{V_r}$ is rainfall volume and **A** is the area of the sub-catchment (roof). The runoff coefficient is a dimensionless parameter that takes into account the volume of water that does not reach the harvester from evaporation, etc. and an acceptable parameter value for this analysis is 0.9 (Federal Highway Administration (FHWA), 1984). The rainfall volume is measured in depth of rainfall for each time step, has units of millimeter and is accessed from historical data. The area of the catchment is the area of the roof and has units of square meters. A conversion of 1/1000 is used to convert the $m^2$*mm units to $m^3$, giving the final value of inflow water units in cubic meters.

## Volume in Cistern

The volume of water stored is calculated based on the volume of the cistern, which is user defined, inflow volume and demand. Cistern spillage must also be taken into account and is the volume of overflow from the cistern when full. There are two ways to calculate the spillage, namely the yield before spillage algorithm (YBS) and the yield after spillage algorithm (YAS). These two algorithms and their associated equations are discussed below. For this analysis, both algorithms will be calculated for each data set. YAS tends to underestimate the available water while YBS tends to overestimate, thus the actual volume of available water from harvesting will fall between these two bounds (Roebuck, 2005).

**YBS Algorithm**

The YBS algorithm calculates the volume of spillage after the daily demand volume has been withdrawn from the storage cistern using three equations. The first calculates the water available for storage during time interval t

$$V_{avail_t} = \left(V_{sw_{t-1}} + I_t - D_t\right) \quad \textbf{(2)}$$

where $\mathbf{V_{sw(t-1)}}$ is the volume of water *actually stored* in the cistern at the end of the previous time interval ($m^3$), $\mathbf{I_t}$ is the volume of inflow into the cistern (harvested rainwater) ($m^3$) and $\mathbf{D_t}$ is the water demand ($m^3$). The second equation calculates the volume of water *potentially* spilled from the cistern

$$V_{sp_t} = V_{avail_t} - V_{cistern} \quad \textbf{(3)}$$

where $\mathbf{V_{avail(t)}}$ is the parameter calculated in equation 2 ($m^3$) and $\mathbf{V_{cistern}}$ is the volume of the cistern ($m^3$). The third equation is a logical statement to assess the volume calculated in equation 3 and set the *actual* spillage and stored volumes

$$\begin{gathered} if\ V_{sp_t} > 0\ then\ V_{sp_t} = V_{sp_t}\ and\ \ V_{sw_t} = V_{cistern} \\ else\ \ V_{sp_t} = 0\ and\ \ V_{sw_t} = V_{avail_t} \end{gathered} \quad \textbf{(4)}$$

This calculation will give a liberal estimate of available water, meaning it will be the upper bound of the actual volume of water.

**YAS Algorithm**

The YAS algorithm calculates the volume of spillage before the daily demand volume has been withdrawn from the storage cistern using two equations. The first calculates the water available for storage during time interval t

$$V_{avail_t} = V_{SW_{t-1}} + I_t \tag{5}$$

where all of the variables are the same as defined for equations 2-4. The second equation is a logical statement to assess the volume available in equation 5 and set actual spillage and stored volumes

$$\begin{gathered} if\ V_{avail_t} > V_{cistern}\ then\ V_{SW_t} = V_{cistern} - D_t\ and\ \ V_{sp_t} = V_{avail_t} - V_{cistern} \\ else\ \ V_{SW_t} = V_{avail_t} - D_t\ and\ \ V_{sp_t} = 0 \end{gathered} \tag{6}$$

This calculation will give a conservative estimate of available water, meaning it will be the lower bound of the actual volume of water available for use.

## Demand

The third piece of information needed for the mass balance calculations is the water demand. For this analysis, water demand is defined as the volume of water needed in the model-housing unit that is suitable to be replaced with RWH. This value can be either a constant daily value, or a changing value based on historical data. Many methods exist for collecting this data, ranging from interviews where users are asked the number of times a day a fixture is used, to collecting data from utility bills (Ghisi and Ferreira, 2007). For this analysis, a survey was composed and given to a contact in Vishakaputnam, India (a large city, 2.0 million persons, near Hyderabad, one of the analyzed cities). A daily typical indoor water demand was determined from the survey information obtained from this contact and his assistants. This value is a constant and will be used as representative demand value for the model-housing unit described above. A sample of the survey can be seen in Appendix A. Several families posted the survey in their residence for a week and recorded the number of times each water consuming activity was performed, along with an approximate volume of water used for each activity. The volume of water consumed each day was totaled and averaged. The range of volume values was from 130-147 liters per day per person, and the average was 134.7 liters. For this analysis a value of 135 liters per day per person of water needed will be used. Given the average Indian household size of 5 persons, a daily water demand for the household is 675 liters (0.675 $m^3$) (Census of India, 2001). The demand value of 135 liters per day per capita fits in well with a review of values found in other studies. See Table 3. Of interest, water for drinking and food preparation makes up approximately 7% of the total household water demand.

## Water Saving Efficiency (WSE)

To determine the effectiveness of RWH to provide water for the household in each region, the WSE will be calculated. The WSE is computed using

$$E_T = \frac{\sum_t^T Y_t}{\sum_t^T D_t} * 100 \quad (7)$$

where $Y_t$ is the yield of the harvester (rainwater supplied) and $D_t$ is the household demand over a specified time period. This percentage is known in the RWH literature and will provide a useful tool to analyze the temporal distribution of the value of the harvesting system (Fewkes, 1999).

## Rainfall Data Source

The data used for analysis is the TRMM_3B42 precipitation intensity statistics collected using the TRMM satellite. TRMM stands for Tropical Rainfall Measurement Mission, a joint data-gathering mission between NASA and the Japanese Aerospace Exploration Agency. The satellite's exact mission was six fold, one of which was to measure precipitation on 3-hour cycles across the planet in order to shed light on the diurnal tropical rainfall patterns (Simpson et al., 1988). The results are over 12 years of nearly hourly precipitation data across most of the planet which is publically accessible on NASA's website (NASA, 2013). The benefit of using the TRMM data is that it provides a standard data source covering the entire country. The satellite instrumentation is composed of six different sensors that each use a different technology to measure precipitation. An algorithm was written which processed all the data fields into one coherent data set that expresses the average precipitation intensities in mm/hr. These data processing results were given a generic name of TRMM Multi-satellite Precipitation Analysis (TMPA) and comprised three different data set products, varying with temporal resolutions. The analysis presented herein used the 3-hourly temporal resolution data which is officially named "TRMM 3-Hourly 0.25 deg. TRMM and Other-GPI Calibration Rainfall Data" and had the short name of "TRMM_3B42" (NASA, 2013). Throughout this analysis the data will simply be referenced as TRMM precipitation data, however, at all times this is actually in reference to the TRMM_3B42 data.

The area of analysis of the TRMM project is divided up into 0.25° by 0.25° (longitude and latitude) and is available in the NetCDF file format. For this analysis, over 36,000 NetCDF files were downloaded, representing 3 hour increments of precipitation data over the analysis period; 1 January 1999 – 30 June 2011. Over 140 years of annual precipitation data were collected to compare the relative volumes of precipitation during the analysis period. The data are annual precipitation total volumes across the entire country of India for 1871 – 2012. The volumes were ranked and the years of analysis position in the ranking were noted. None of the years of analysis were in the bottom fifth of data, four were in the second fifth, two were in the third fifth, three were in the forth firth and four were in the top fifth. While the years of analysis data are slightly skewed towards the higher volume years, overall the data are fairly well distributed between dry and wet years. This leads to high confidence that the years of analysis properly represent the typical long term Indian precipitation volumes. The area of study was confined to a rectangular grid that covered all of India starting at the southwest corner, 63.875°, 4.875° and extending up to the northeast corner, 94.875°, 36.625°.

A MATLAB script was written and used to extract the appropriate data from the 36,000 NetCDF files and saved into a Microsoft Excel file. A separate run of the script needed to be executed for each grid cell of precipitation data, thus in turn creating a separate spreadsheet for each city's precipitation. Table 4 details the latitude and longitude coordinates for each of the six analyzed cities along with the cell location of that city's center, from the NetCDF files. Data were extracted from the listed cell for each city.

Upon completion of each MATLAB script run, a single Microsoft Excel file was compiled which contained a date and time stamp every 3 hours along with the intensity of precipitation over that 0.25° x 0.25° section of the earth for a 3 hour time period. In order to test the MATLAB script accuracy, ten random precipitation events for each file were chosen and the source NetCDF file was consulted to check if the correct data was entered into each of the checked events. If any errors had been located, a more extensive data check would have been completed, however, all data points passed with zero errors.

Two analyses were completed to check the accuracy of the TRMM precipitation data with recorded ground precipitation gage data. Hourly and/or daily precipitation data are not generally available in any region of India. Nevertheless, the Indian government through the Indian Institute of Tropical Meteorology (a branch of the Ministry of Earth Sciences) has provided monthly precipitation averages for eight geographic regions of the country. To compute the averages, the country was divided up into eight geographic regions, and an average of all the rain gages in that region was computed for each month. Given the fairly large regions over which the averages are computed, and the great variability that naturally exists of rainfall volumes over even fairly small areas, this analysis seeks similarity in precipitation patterns, not necessarily exactness in depths. Figure 5 shows the comparison of the extracted TRMM data, multiplied by 3 hours and averaged over the month, and the provided monthly averages for the year 1999. Note the similarity in rainfall patterns, meaning the times when the volume increases and conversely decreases.

The second analysis completed to check the accuracy of the TRMM data with instrument-recorded measurements takes the annual averages of precipitation (again multiplied by 3 hours to match units) of the extracted TRMM data and compares the averages with published annual averages for each city. The published values are reported for a city, thus the spatial resolution is much higher than the previous comparison. Caution needs to still be exercised as the published values are still computed averages of many rain gages, while the TRMM data is recording of precipitation for one exact geographic location (0.25° by 0.25°). Data for Bangalore could not be found. See Table 5 for the values and the computed relative error. Three of the cities are very close, falling within 12% of the recorded values, with two of them falling within 9%. The other two are not as close, falling within 22% and 26% relative error. Considering the variability introduced from computing averages of data over large areas, these computations instill a fair amount of confidence that the TRMM precipitation data do indeed correctly represent the actual precipitation patterns and volumes.

## Units of Data Measurement and Volume Calculations

The data are recorded as rainfall intensity (mm/hr) according to the NC_info page of the NetCDF files also on the TRMM_3B42 product summary page (NASA, 2013). Given that the data are an average value of multiple measurements, using multiple different recording methods, during the 3-hour increments and not a point measurement, the average intensity just needs to be multiplied by the time period. To calculate the total volume of precipitation (in depth units) over each time period, the intensity just needed to be multiplied by 3 hours. To calculate the total volume of water collection by roof catchment, the volume of precipitation needs to be multiplied by the area of the roof catchment and the runoff coefficient (0.9). This is the inflow volume calculation described above in the “Inflow Volume” section. This will give a volume of water that can be collected during that 3-hour increment. This calculation was programmed into a MATLAB script and was able to use all the extracted TRMM data to determine the daily inflow volumes. A daily time step for calculations is of interest, thus the eight volumes for each day (data are in 3 hour increments) are summed to give units of $m^3$/day. To test the accuracy of this MATLAB script, another ten random dates were chosen for each city of analysis, and the inflow volume calculation was performed by hand. All the inflow volumes matched exactly for each city, giving very high confidence the script was performing the correct calculations.

**Rainfall Distributions by City**

According to the Indian Meteorological Department, the country experiences annual monsoonal precipitation patterns over at least 85% of the country (National Climate Centre, 2013). The official monsoon season starts 1 June and ends 1 September. In order to analyze the different rainfall distributions of each analyzed city, the following ratio was calculated

$$dry - to - wet\ season\ ratio = \frac{\sum_{Sept\ 2}^{May\ 31} Precip}{\sum_{June\ 1}^{Sept\ 1} Precip} \tag{8}$$

where the sum of the nonmonsoonal season (October to May) precipitation and the monsoonal (June to September) precipitation volumes were analyzed. These ratios will henceforth be referred to as dry-to-wet season ratio. The lower the number, the more seasonal the precipitation is in that area; meaning the city has a poorly distributed precipitation pattern with the majority of the rain occurring between the months of June and August leaving the rest of the year extremely dry. The averages of annual data were used in the calculation. Table 6 has the calculated values.

From the dry-to-wet ratios, Bangalore and Srinagar would be expected to have the greatest RWH efficiency; however, once the total precipitation is taken into account Srinagar is unlikely to receive sufficient rainfall to make RWH worthwhile. Kolkata and Mumbai are the leaders in total annual precipitation, making them good candidates for RWH.

## Storage Cistern Volumes and Catchment Areas

A range of both RWH cisterns: 757 L, 1,893 L, 3,785 L, 9,464 L and 18,927 L; and catchment areas: 10 $m^3$, 21 $m^3$, 50 $m^3$ and 100 $m^3$; were analyzed in order to better understand the effects of different variable sizes on the Water Saving Efficiency (WSE) for each city. These variations allows for a sensitivity study to further understand the relationship between the cistern sizes, catchment areas and the WSE.

## Data Analysis

Three inputs are needed for the mass balance calculation, namely the inflow volume, the cistern volume and the daily water demand. The daily water demand is known (see Water Demand Determination), the inflow volume for each time period is recorded (see Units of Data Measurement and Volume Calculations) and the cistern volumes used for the analysis have been decided (see Storage Cistern Volumes). With the mentioned inputs, the volume of water stored in the cistern, and the volume of water from cistern overflow can be calculated for each time step. A MATLAB script was written to record this information on a daily basis for each of the six cities of analysis, using both the YBS and the YAS algorithms. The YBS is the best-case scenario, the maximum possible volume of water will be stored and minimum volume lost, while the YAS is the worst-case scenario. The results presented are based on the YAS algorithm, giving the smallest volume of water possible based on the inputs to the calculation

Two inputs are needed for the WSE calculation, namely RWH yield and household demand. The yield is the sum of the volume of water actually supplied to the household, or volume of water out of the cistern over a specific time period. The demand is the sum of the volume of water needed by the household over the same time period. The time increment for the initial calculation was 1 month. This was calculated with a MATLAB script and the results were checked with a spreadsheet. The maximum possible value was 100%. The monthly values were averaged over the 12 year time period, Jan-Jun 2011 was excluded to give an equal weight to each month, and those values were averaged. This resulted in an average value across the entire period of analysis for a specific city with a specific catchment size and cistern volume. This same set of calculations was performed for each city 20 times (4 catchment sizes * 5 cistern volumes).

Table 2: Cities of analysis with
population and climatic region

| City | Population (Million) | Region |
|---|---|---|
| Mumbai | 12.5 | Tropical Wet and Dry |
| Delhi | 11.0 | Semi-arid |
| Bangalore | 8.4 | Semi-arid |
| Hyderabad | 6.8 | Tropical Wet and Dry |
| Kolkata | 4.5 | Tropical Wet and Dry |
| Srinagar | 1.2 | Montane |


go

Figure 2: India with cities of analysis marked. Map data: Google, US Department of State Geographer


Figure 3:  Typical middle class living accommodations


Figure 4:  Aerial view of model building, with polygon used for calculating area in blue.
Note: there are four similar buildings packed tightly together.
Map data: Google, DigitalGlobe

Table 3: Literature comparison of Indian daily water demand per person

| Method/ Study | Volume (L) |
|---|---|
| Surveys for this analysis | 135 |
| Tata Institute of Social Science (Nandgaonkar, 2005) | 78-115 |
| 2006 UN Human Development Report (United Nations Development Programme (UNDP), 2006) | 135 |
| Falkenmark minimum for basic needs (Falkenmark & Widstrand, 1992) | 100 |

Table 4: Geographic location of each analyzed city along with NETcfd file grid location

| City | Lat | Long | Grid Cell |
|---|---|---|---|
| Mumbai | 18.975 | 72.826 | (58,38) |
| Delhi | 28.610 | 77.230 | (96,54) |
| Bangalore | 12.967 | 77.567 | (33,56) |
| Hyderabad | 17.366 | 78.476 | (51,59) |
| Kolkata | 22.567 | 88.367 | (72,99) |
| Srinagar | 34.090 | 74.790 | (118,45) |

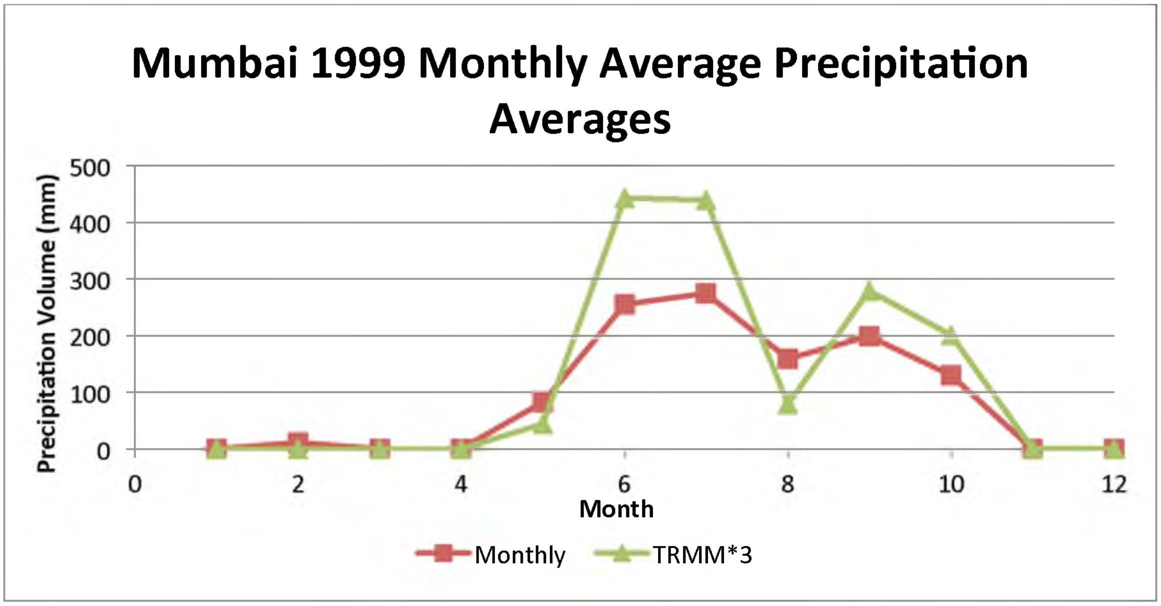


Figure 5: Comparison of the extracted TRMM precipitation data for Mumbai, summed over each month, with regional monthly averages.
Data source: (Ministry of Earth Sciences, Govt. of India, 2006)

Table 5: Comparison of annual averaged TRMM data with published annual data on a city averages level.
Data sources: (Centre for Science and Environment, 2013; Ministry of earth Sciences, Govt of India, 2013)

| City | TRMM Avg | Reference | Rel Error |
|---|---|---|---|
| Bangalore | 1100.8 | N/A | N/A |
| Delhi | 727.5 | 797.3 | -0.087 |
| Hyderabad | 909.4 | 812.5 | 0.119 |
| Kolkata | 1531.8 | 1641.4 | -0.067 |
| Mumbai | 1782.9 | 2422.1 | -0.264 |
| Srinagar | 546.0 | 703.6 | -0.224 |

Table 6: Dry-to-wet ratios and total precipitation for cities of analysis

| City | Dry-to-Wet Ratio | Total Precipitation (mm) |
|---|---|---|
| Bangalore | 1.77 | 1101 |
| Delhi | 0.55 | 728 |
| Hyderabad | 0.70 | 909 |
| Kolkata | 0.89 | 1532 |
| Mumbai | 0.29 | 1783 |
| Srinagar | 1.37 | 546 |

## RESULTS AND DISCUSSION

Six tables along with six figures were created in order to organize the data and ease analysis of the WSE results for each city. Tables 7-12 present the calculated WSE for each category of varying catchment size and cistern volume. Figures 6-11 were created using the mesh command in MATLAB, and are simply a 3D graphic of the table data. The two horizontal axes are the catchment areas (varying from 0 to 100 $m^2$) and cistern sizes (varying from 0 to 20,000 L), while the vertical axis is the WSE. All of the vertical axes on the six plots were normalized to show 0-50% to aid in comparison of WSE across the cities of analysis.

The six cities can be organized into four categories of efficiency: most efficient (WSE $\geq$ 50% for largest area and cistern), midrange (35% $\leq$ WSE < 50% for largest area and cistern), low midrange (20 < WSE < 35% for largest area and cistern) and least efficient (WSE $\leq$ 20% for largest area and cistern). Srinagar is the least efficient as it has values ranging from 2% for the smallest catchment and cistern to 20% for the largest. Kolkata's efficiency ranges from 5% to 50%, resulting in the highest WSE values making it the most efficient. Bangalore and Mumbai have midrange values ranging from 4% to 39% and 6% to 40%, respectively. Lastly, Delhi and Hyderabad are low midrange with efficiencies of 3% to 25% and 3% to 32%, respectively.

When comparing the efficiency categories of each city to the dry-to-wet ratios and total precipitation analysis (Table 6), some interesting correlations can be made. Firstly, the WSE increases with increases in catchment area and cistern volume. This is a result of the RWH system being able to collect a larger volume of water given a larger inflow volume (increased catchment area) and larger storage capability. In terms of individual city analyzed, Srinagar had a high dry-to-wet ratio of 1.37, which is the second highest, however, the city performed poorly under RHW analysis making it the least efficient. The poor performance of Srinagar was a result of very low precipitation throughout the year, totaling to only 546 mm, meaning the volume of precipitation during the year is not sufficient to make RWH efficient. The performance of Srinagar showed that even if precipitation is well distributed throughout a year (has a high dry-to-wet ratio), a certain volume threshold of annual precipitation is needed to make RWH worthwhile. Conversely to the results of Srinagar, Mumbai performed moderately well in the WSE, however, the dry-to-wet ratio from Mumbai is low (0.29). The high performance of Mumbai was a result of receiving a very large volume of precipitation in a year (1784 mm). It was surmised from this information that the high WSE is a result of the wet season having very high values, likely near 100%, which raised the average poor performance through the rest of the year. The performance of Mumbai led to the conclusion that poorly distributed precipitation (poor dry-to-wet ratios) can be offset by large annual volumes of precipitation.

Kolkata and Bangalore had very interesting results that need to be compared together. Kolkata had a moderate dry-to-wet ratio (0.89), while Bangalore had the highest dry-to-wet ratio (1.77). Despite Bangalore having a dry-to-wet ratio nearly double that of Kolkata, both cities performed moderately well on the WSE analysis. The key was that Kolkata received nearly 50% more precipitation than Bangalore, with Kolkata at 1532 mm and Bangalore at 1101 mm. This again led to the conclusion that lower dry-to-wet ratios can still lead to better than expected WSE results, if the volume of precipitation is higher. Lastly, both Delhi and Hyderabad performed poor on the WSE which was not a surprise given they both had low dry-to-wet ratios and low precipitation.

In an effort to liken the results of this study with previous works, a study on RWH WSE in different climatic regions across the US was used for comparison. The study (Steffen study) looked at 23 cities in 7 different climatic regions and analyzed the WSE if RWH was implemented for various different uses (Steffen, et al., 2013). For this comparison, the total indoor water use scenario was analyzed. The study presented the results for one tank size per region, but is not necessarily the same tank size across all regions. For comparison, cities of similar climate and similar tank size from this study were analyzed. The study performed the analysis for an 11 hectare (110,000 $m^2$) area with 100 housing units, this reduced to 1,100 $m^2$ catchment area for each house. For comparison purposes, the largest area of analysis from this study was used, which is 100 $m^2$.

The wettest climates in the Steffen study were the southeast, east coast and pacific northwest regions, which were comparable to Mumbai, Kolkata and Bangalore. The drier (semi-arid) climates in the Steffen study were the Southwest and West Coast regions which were comparable to Delhi and Bangalore. Lastly, the mountain climate in the Steffen study was the mountain west region, which was comparable to Srinagar. A comparison of each of these comparable regions with similar catchment area and cistern volume is presented in Table 13. The results between the two studies do not match perfectly for each comparable region; however, the drier two regions only differ by less than 10%. The wet region varies more with this study, having ~20% lower efficiency values, but this was likely caused from the wide range and variability in the tank sizes. While the WSE values between the two studies do not match up exactly, they were fairly close and validated each other.

A study of Tables 6-12 brings forth some important realizations about the sizing of the cisterns relative to the catchment areas and the precipitation patterns for an area. Ignoring one small exception in Kolkata, the size of the tank had no effect on the WSE when the catchment area is small (10 $m^2$ in this case). When a catchment area was small, the total volume of water available for storage was also small, making a large tank unnecessary. It was noticed that this was true across all the climatic regions analyzed, making the tank size independent of the climatic region for small catchment areas. This led to the conclusion that the most appropriate size of cistern for a 10 $m^2$ catchment area is 757 L. In this sense, the most appropriate size is trying to match the most benefit to the house (high WSE), with the smallest cistern size possible. A smaller cistern is generally preferred because it will cost less to install and repair, the system will weigh less and will have a higher likelihood of being installed in new development.

As the catchment area increased, the WSE began to vary with differing cistern sizes, increasing as the size of the cistern increases. The WSE rate of increase was different for each city, bringing out the connection of the WSE and cistern size to precipitation patterns. For example, on the second largest catchment area (21 $m^2$), the WSE varied very little, by 0-1%, on all the cities except Kolkata and Mumbai. Both

Kolkata and Mumbai were in the tropical wet and dry climatic region, which has volumes of 1532 mm and 1783 mm, respectively. These precipitation volumes are approximately 50-300% larger than all the other cities listed. Interestingly, the WSE variance for Mumbai was two times larger than that of Kolkata, with Mumbai varying from 9-14% and Kolkata varying from 10-12%. The reason for Mumbai's more rapid WSE increase for the 21 $m^2$ catchment area is not immediately obvious, as the dry-to-wet ratio for Mumbai is 1/3 as large as Kolkata's and the total volume of precipitation for Mumbai is only 14% larger. The overall most appropriate size of the cistern for the 21 $m^2$ catchment area was still 757 L for all cities except perhaps Mumbai which had a jump from 9% to 12% for the second largest cistern (1893 L) but only a jump from 12% to 14% across the next three cistern sizes.

The WSE rate of increase for the two largest catchment areas, 50 and 100 $m^2$, continued to follow the same trends discussed for the 21 $m^2$ area, except the increases were larger. For the 50 $m^2$ catchment area, the increase varied from 6% to 8% for Bangalore, Delhi and Hyderabad, but varied by 14% for Kolkata and 18% for Mumbai. For the 100 $m^2$ catchment area, the increase varied from 15% to 22% for Bangalore, Delhi and Hyderabad, but varied by 31% for Kolkata and 25% for Mumbai. Srinagar had low rates of increase on the two largest catchments at 3% and 9%, respectively. The most appropriate cistern size for the two larger catchments is not nearly as obvious as the range of WSE values are much greater.

Another interesting trend between the cistern sizes, catchment areas and precipitation patterns for an area was found by noticing the different rates of increase of the WSE between each cistern volume for a given catchment size. The general trend was to have large increases in the WSE up to a certain point, and then the increases decreased and in some cases leveled out. For example, in the case of Bangalore 50 $m^2$ catchment area, the WSE were 13%, 17%, 19%, 20%, 20% for the respective increasing cistern sizes. This showed the exact trend mentioned, where the WSE increased greatly at the beginning and then leveled out, jumping 4% between the smallest tanks, 2% between the second and third smallest, then 1% and 0%. In contrast, the WSE did not change at all between the cistern sizes for the Bangalore 10 $m^2$ and 21 $m^2$ catchment areas. In another contrast for the Bangalore 100 $m^2$ catchment size, the WSE increased by 7%, 5%, 4% and 3%, respectively, for the increasing cistern sizes, while the incremental increases decreased, the values never leveled off. This suggested if there were more cistern size options, the increases would have leveled off, however, any larger cistern sizes would be extremely unrealistic being too large for a single family-housing unit. Keeping this trend in mind helped to recommend the most appropriate cistern size for the larger two catchment sizes in each city. The most appropriate cistern size recommendation is based on an inflection point estimate where the data lied on a plot of WSE versus tank size. This provided the most benefit with the smallest possible tank size as discussed above. These cistern sizes are presented in Table 14.

The most appropriate cistern sizes were used in an effort to understand the seasonal performance of the RWH systems. For each city and catchment area, the WSE data for the most appropriate cistern size was averaged on a monthly basis and plotted. Figures 12 through 17 show these results. A seasonal trend was evident at least to some extent in all the plots, but was much more obvious in some plots than others. Keeping the dry-to-wet ratio in mind while analyzing the figures helped to make sense of the trends.

The most obvious feature was Bangalore and Srinagar had the most level efficiency trends, while the rest of the cities tended to have very low values at the beginning of a year, followed by a steep upward trend staring in April or May. This trend formed a dome of much higher efficiency values which generally peaked in August and returned to near zero values in October or November. The nondomed trends of Bangalore and Srinagar pointed to relatively even distributed precipitation patterns throughout the year, which is proved to be true when looking at the dry-to-wet ratios. Bangalore and Srinagar have the two highest dry-to-wet ratios of 1.77 and 1.37, respectively. Meanwhile Mumbai appeared to have the most poorly distributed precipitation patterns, as was seen from Figure 16. Mumbai had very low efficiency values from January to May, then in May the efficiency rapidly increased, causing a very steep sided dome rising all the way to 100% efficiency by the beginning of July, staying at 100% until September, then falling very rapidly during October and November. The poor precipitation distribution of Mumbai was confirmed with the dry-to-wet ratio of 0.29, which was substantially smaller than the rest of the values. As pointed out above, the fairly good performance of Mumbai in the overall WSE was caused from the very high values during the wet months, which pulled the overall annual average up.

In contrast, Delhi, Hyderabad and Kolkata had very similar looking plots, with slowly rising, but still very low efficiency values from January to April. Starting in April the efficiencies rose rapidly, but much slower than Mumbai. Each of the cities efficiencies fell at different times with Delhi falling to near zero values in October, Hyderabad did not fall until November and Kolkata fell in December. This correlated well with the dry-to-wet ratios for each city. Delhi had a value of 0.55, the smallest values of these three cities since it rose at the same time, but fell earlier. Hyderabad and Kolkata had dry-to-wet ratios of 0.70 and 0.89, respectively. All three of these cities had; fairly low dry-to-wet ratio values because of the near zero efficiencies during the first part of the year. With the exception of Srinagar, all of the analyzed cities have the vast majority of the RWH benefit occurring between the months of April and November, leading to the conclusion that the harvesters could be taken out of commission during the months of December to March, and the overall benefit would not be significantly affected.

A simple cost analysis was performed to give a very coarse view of the set-up costs of a typical RWH system. In the beginning of 2013 the US Environmental Protection Agency (EPA) released a literature review of RWH studies, which included a set of simple cost calculation tools (EPA, 2013). The cost of a cistern was typically between $1.50 - $3.00 per gallon of storage, depending on the material, size and shape. The larger a tank gets, the lower the cost per gallon. There are 3.79 liters in a gallon, making the cost of a harvester approximately $0.39 per liter, using the assumption that materials would be on the low end of the projected costs in India. This would make the costs of the installation of the RWH systems between $300 for the 757 L system and $3,500 for the 9464 L cistern. Table 15 breaks down the cost of the system set up for each household assuming a catchment area of 21 $m^2$, the most appropriate cistern volume is used, and the lifetime of the system is 20 years. The costs are presented in United States dollar amounts per cubic meter of water saved. The costs range from $0.67 - $1.50. Further analysis should be conducted in order to see if the pricing structure would be the same in India, and to see how this cost burden would affect a typical household.

A very simple spillage analysis was performed; the purpose of this analysis was to see the approximate benefit of diverting all the spillage from the RWH cistern for the purpose of GWR. The benefit in this case was defined as the volume of water that could be used for GWR. A new WSE was calculated for each city, based solely on the GWR volume, assuming all the water used for GWR would later be accessible to the family for indoor use. This calculated WSE would be a boost to the previous WSE calculations, meaning it could be added to the WSE value from RWH alone. This analysis was performed for each city, for the most appropriate sized cistern with the 21 $m^2$ catchment area. As can be observed in Table 16, approximately 2-11 $m^3$ of water per household could be used for GWR in the differing cities, excluding Srinagar, and a WSE boost of 0.8% - 4.4% could be experienced for each city. Srinagar was excluded given the extremely small benefit, 0.3 $m^3$, and the low WSE values, making the option of RWH not a likely choice for indoor water use. Following the results of the previous analyses performed, Mumbai and Kolkata provided the largest benefits of 10.9 $m^3$ and 4.9 $m^3$, respectively, and a WSE boost of 4.4% and 2.0%. The reason for Mumbai providing more than double the benefit of Kolkata, while only having 14% more average precipitation volume in a year is unknown, and deserves more analysis. Bangalore, Delhi and Hyderabad all had approximately the same benefits with values of 1.9 $m^3$, 2.1 $m^3$ and 1.9 $m^3$, respectively, and each had a WSE boost of 0.8%. The similar benefits of these three cities are not surprising as they all receive approximately the same volume of precipitation. Whether installing a GWR system is worthwhile for these potential benefits is currently unknown.

Table 7: Summary of WSE (%) for varying catchment sizes and cistern sizes in Bangalore

| Catchment Size (m3) | Cistern Size (L) | | | | |
|---|---|---|---|---|---|
| | 757 | 1893 | 3785 | 9464 | 18927 |
| 10 | 4 | 4 | 4 | 4 | 4 |
| 21 | 8 | 8 | 8 | 8 | 8 |
| 50 | 13 | 17 | 19 | 20 | 20 |
| 100 | 18 | 25 | 30 | 36 | 39 |

Table 8: Summary of WSE (%) for varying catchment sizes and cistern sizes in Delhi

| Catchment Size (m3) | Cistern Size (L) | | | | |
|---|---|---|---|---|---|
| | 757 | 1893 | 3785 | 9464 | 18927 |
| 10 | 3 | 3 | 3 | 3 | 3 |
| 21 | 5 | 5 | 6 | 6 | 6 |
| 50 | 8 | 11 | 12 | 13 | 13 |
| 100 | 11 | 16 | 20 | 24 | 25 |

Table 9: Summary of WSE (%) for varying catchment sizes and cistern sizes in Hyderabad

| Catchment Size (m3) | Cistern Size (L) | | | | |
|---|---|---|---|---|---|
| | 757 | 1893 | 3785 | 9464 | 18927 |
| 10 | 3 | 3 | 3 | 3 | 3 |
| 21 | 6 | 7 | 7 | 7 | 7 |
| 50 | 11 | 14 | 16 | 16 | 16 |
| 100 | 15 | 21 | 25 | 29 | 32 |

Table 10: Summary of WSE (%) for varying catchment sizes and cistern sizes in Kolkata

| Catchment Size (m3) | Cistern Size (L) | | | | |
|---|---|---|---|---|---|
| | 757 | 1893 | 3785 | 9464 | 18927 |
| 10 | 5 | 6 | 6 | 6 | 6 |
| 21 | 10 | 11 | 12 | 12 | 12 |
| 50 | 15 | 21 | 25 | 27 | 28 |
| 100 | 20 | 29 | 36 | 45 | 50 |

Table 11: Summary of WSE (%) for varying catchment sizes and cistern sizes in Mumbai

| Catchment Size (m3) | Cistern Size (L) | | | | |
|---|---|---|---|---|---|
| | 757 | 1893 | 3785 | 9464 | 18927 |
| 10 | 6 | 6 | 6 | 6 | 6 |
| 21 | 9 | 12 | 13 | 13 | 14 |
| 50 | 13 | 18 | 21 | 27 | 30 |
| 100 | 16 | 22 | 26 | 34 | 40 |

Table 12: Summary of WSE (%) for varying catchment sizes and cistern sizes in Srinagar

| Catchment Size (m3) | Cistern Size (L) | | | | |
|---|---|---|---|---|---|
| | 757 | 1893 | 3785 | 9464 | 18927 |
| 10 | 2 | 2 | 2 | 2 | 2 |
| 21 | 4 | 4 | 4 | 4 | 4 |
| 50 | 8 | 10 | 10 | 10 | 10 |
| 100 | 12 | 16 | 19 | 20 | 20 |

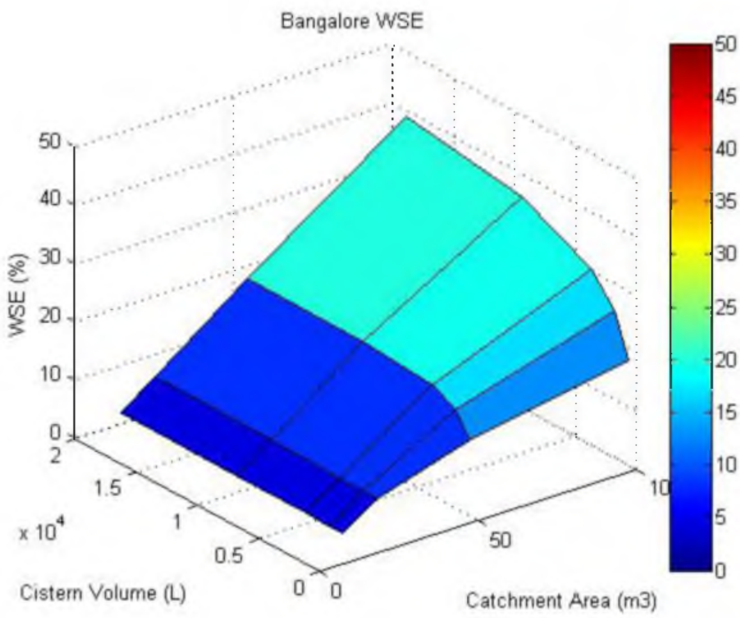


Figure 6: Bangalore WSE values for varying catchment areas and cistern volumes

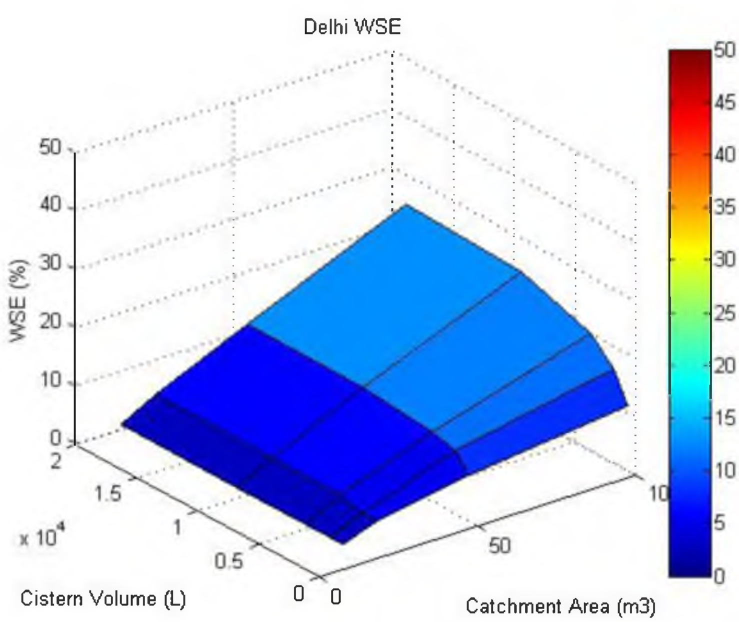


Figure 7: Delhi WSE values for varying catchment areas and cistern volumes

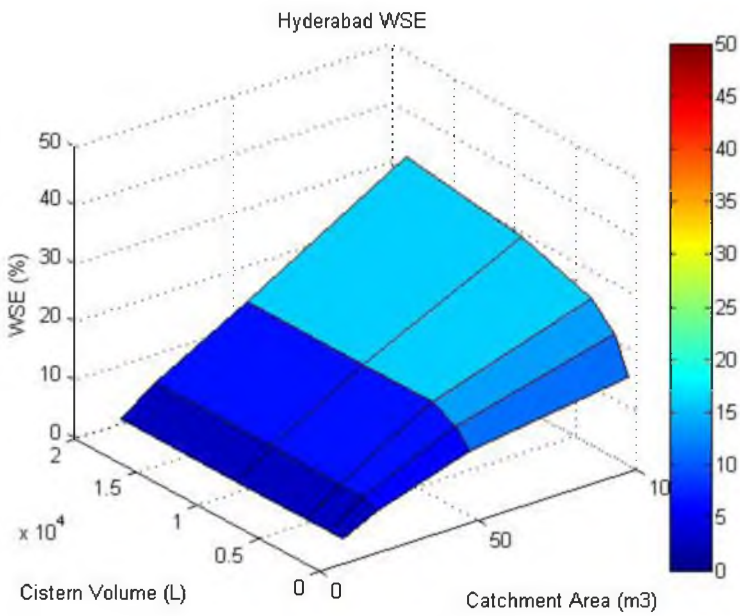


Figure 8: Hyderabad WSE values for varying catchment areas and cistern volumes

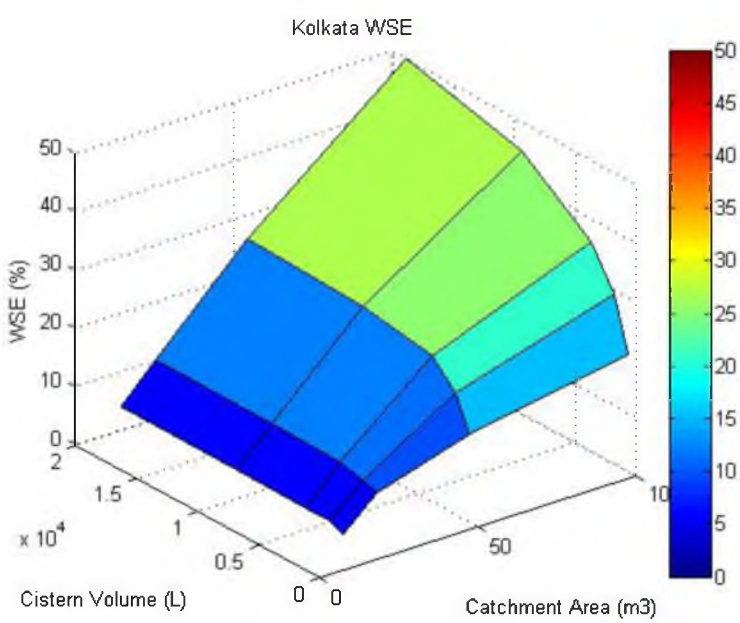


Figure 9: Kolkata WSE values for varying catchment areas and cistern volumes

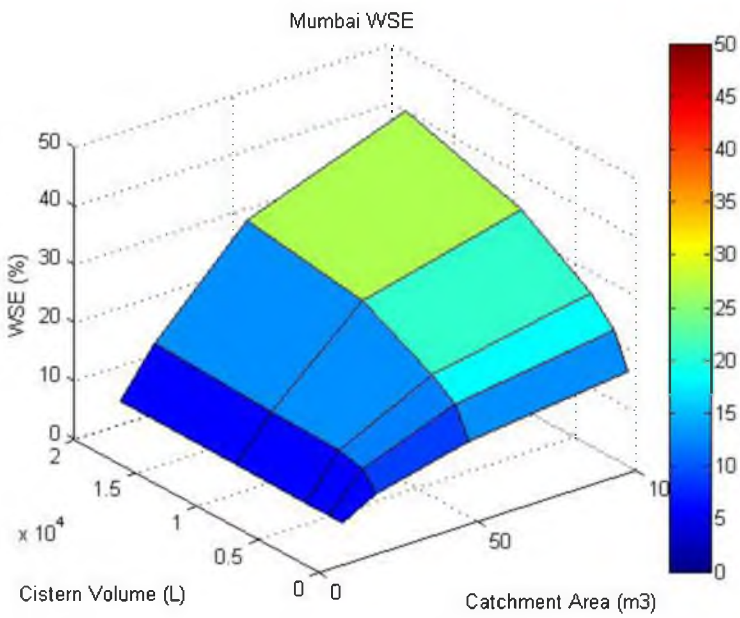


Figure 10: Mumbai WSE values for varying catchment areas and cistern volumes

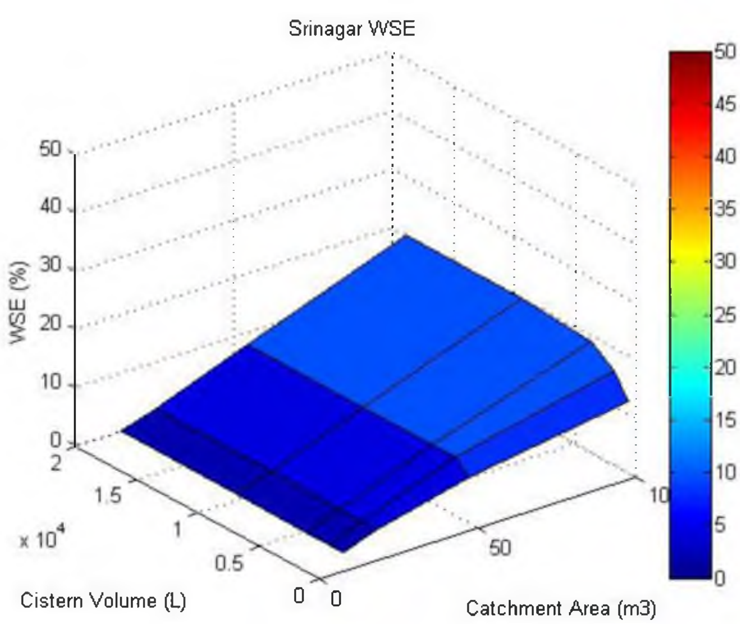


Figure 11: Srinagar WSE values for varying catchment areas and cistern volumes

Table 13: WSE Results comparison between Steffen, et al., and this paper for areas of comparable climatic region, catchment area and cistern volume

| Steffen Results | | | Stout Results | | | |
|---|---|---|---|---|---|---|
| Region | Cistern (L) | WSE | City | Region | Cistern (L) | WSE |
| Southeast | 5,678 | 56% | Mumbai | Tropical Wet & Dry | 3,785 - 9,464 | 30-36% |
| East Coast | 4,732 | 57% | Kolkata | Tropical Wet & Dry | 3,785 - 9,465 | 26-34% |
| Pacific Northwest | 6,814 | 59% | Bangalore | Tropical Wet & Dry | 3,785 - 9,466 | 36-45% |
| Southwest | 757 | 8% | Delhi | Semi-arid | 757 - 3,785 | 11-20% |
| West Coast | 3,028 | 16% | Bangalore | Semi-arid | 758 - 3,785 | 18-30% |
| Mountain West | 946 | 19% | Srinagar | Montane | 757 | 12% |

Table 14: Recommended cistern volume for catchment size

| City | Catchment Area (m2) 10 | 21 | 50 | 100 |
|---|---|---|---|---|
| Bangladore | 757 | 757 | 3785 | 9464 |
| Delhi | 757 | 757 | 3785 | 9464 |
| Hyderabad | 757 | 757 | 3785 | 9464 |
| Kolkata | 757 | 757 | 3785 | 9464 |
| Mumbai | 757 | 1893 | 9464 | 18927 |
| Srinagar | 757 | 757 | 1893 | 3785 |

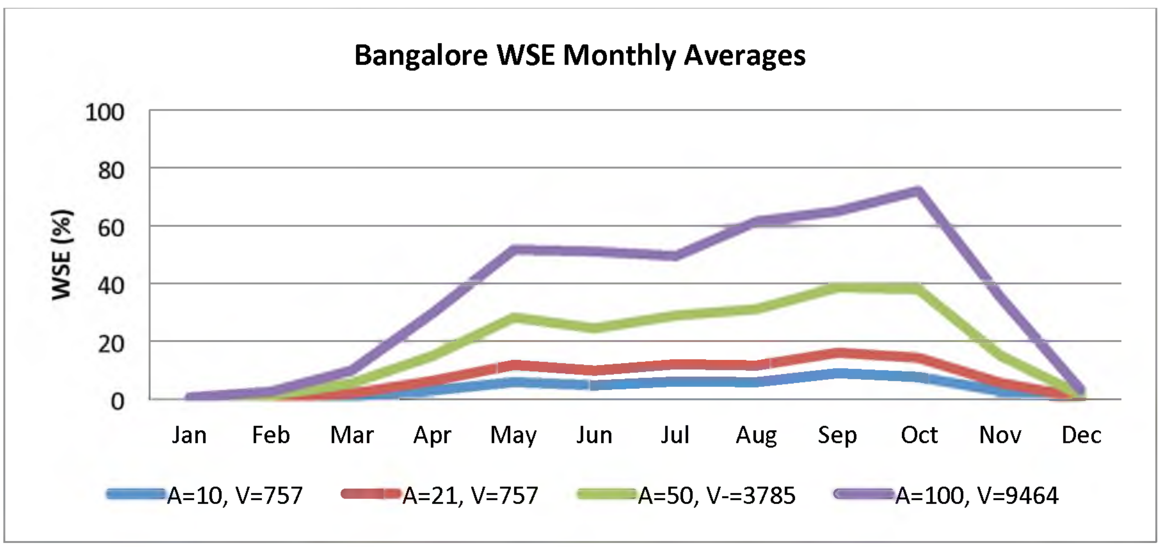


Figure 12: Bangalore WSE monthly averages for each most appropriately sized cistern for the given catchment area

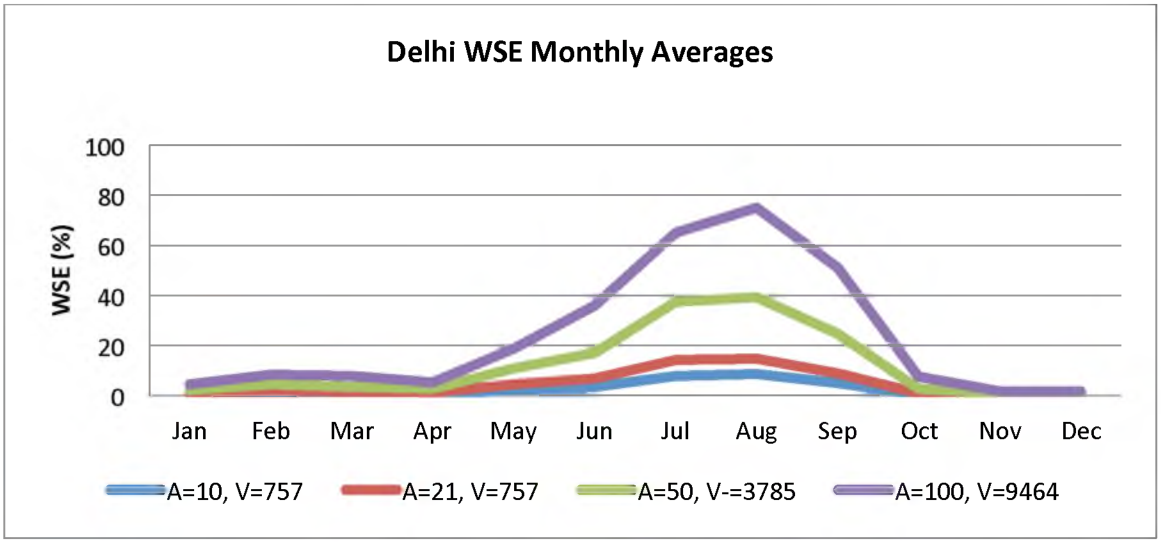


Figure 13: Delhi WSE monthly averages for each most appropriately sized cistern for the given catchment area

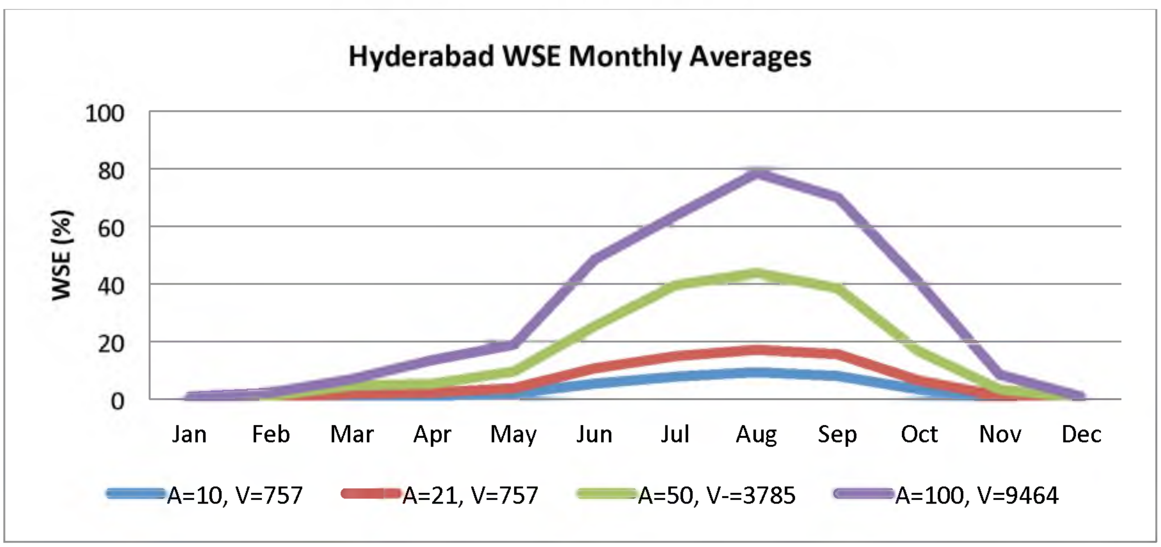


Figure 14: Hyderabad WSE monthly averages for each most appropriately sized cistern for the given catchment area

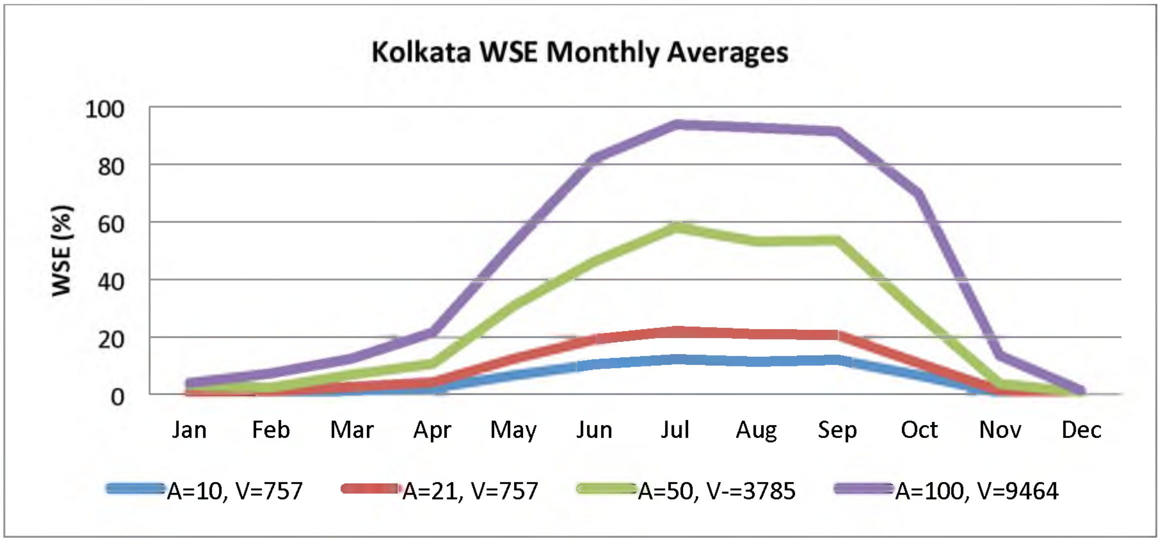


Figure 15: Kolkata WSE monthly averages for each most appropriately sized cistern for the given catchment area

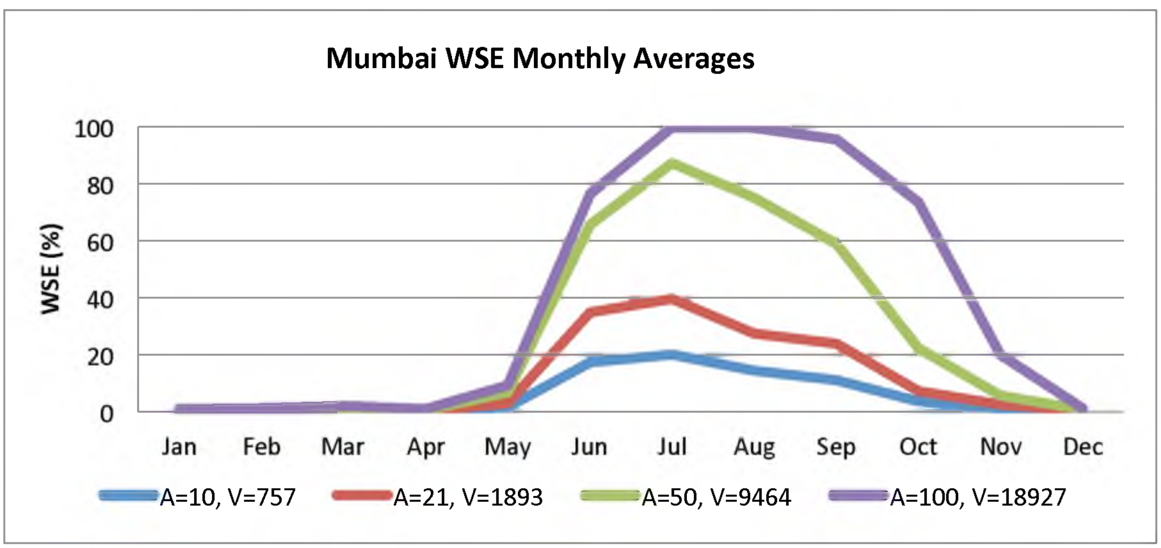


Figure 16: Mumbai WSE monthly averages for each most appropriately sized cistern for the given catchment area

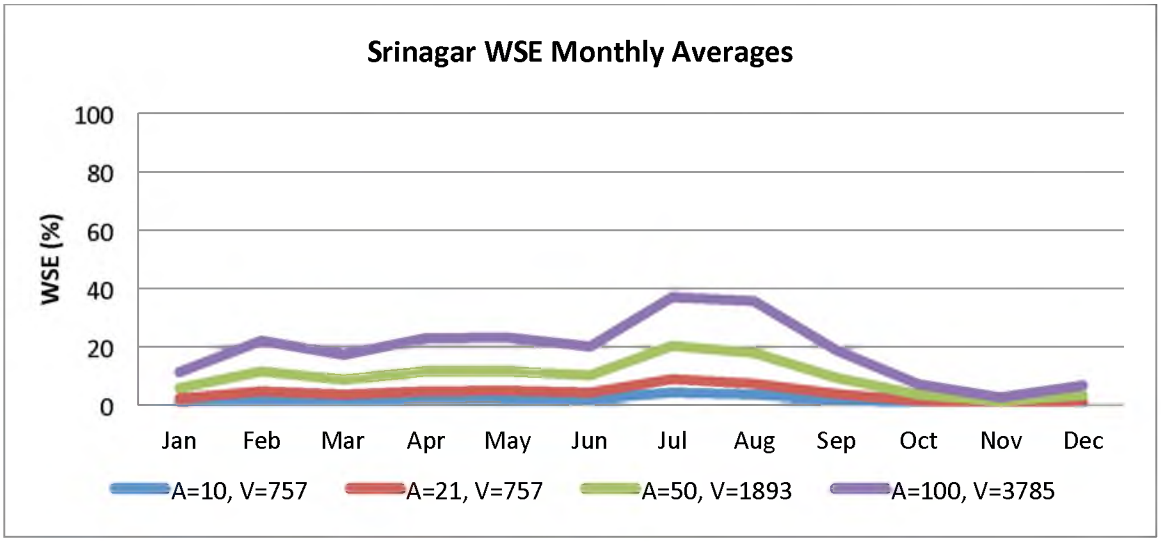


Figure 17: Srinagar WSE monthly averages for each most appropriately sized cistern for the given catchment area

Table 15: Cost of most appropriate cistern for each household for each city assuming 21 $m^2$ catchment area

| City | Cost of Most Appropriate Cistern | WSE | Water Saved per Year (m3) | Water Saved over 20 Years (m3) | Lifetime Cost Per m3 |
|---|---|---|---|---|---|
| Bangalore | $295.23 | 8% | 19.71 | 394.20 | $0.75 |
| Delhi | $295.23 | 5% | 12.32 | 246.38 | $1.20 |
| Hyderabad | $295.23 | 6% | 14.78 | 295.65 | $1.00 |
| Kolkata | $738.27 | 11% | 27.10 | 542.03 | $1.36 |
| Mumbai | $295.23 | 9% | 22.17 | 443.48 | $0.67 |
| Srinagar | $295.23 | 4% | 9.86 | 197.10 | $1.50 |

Table 16: Volume of water available for GWR per household
if all cistern spillage was used for this purpose,
for the most appropriate cistern volume
on the 21 $m^2$ catchment and
associated WSE boost

| City | Volume (m3) | Water Demand (m3) | WSE |
|---|---|---|---|
| Bangalore | 1.9 | 246.4 | 0.8% |
| Delhi | 2.1 | 246.4 | 0.8% |
| Hyderabad | 1.9 | 246.4 | 0.8% |
| Kolkata | 4.9 | 246.4 | 2.0% |
| Mumbai | 10.9 | 246.4 | 4.4% |
| Srinagar | 0.3 | 246.4 | 0.1% |

# CONCLUSIONS

A spatial and temporal analysis of precipitation patterns across the country of India were analyzed in order to assess the suitability of using RWH as a means for getting indoor water to households. Suitability was determined using the WSE equation. NASA TRMM satellite project data were used to determine the precipitation patterns needed for analysis. Several models were created from scratch (see Appendix) to extract the TRMM data for each city of analysis, perform a mass balance calculation to analyze several different sizes of rain cisterns while varying catchment area, and calculate the WSE on an annual basis for each city. The analysis was performed over a 12.5 year (150 month) time period.

Most of India experiences very seasonal precipitation patterns on account of annual monsoons. To better understand the effects of these monsoons, a dry-to-wet ratio was created which took the ratio of the total precipitation during the dry months (September – May) and the total precipitation of the wet months. The ratio varied from 0.29 to 1.77 and the total precipitation varied from 546 mm to 1783 mm. This ratio along with the average annual total precipitation volume was used to analyze the reasoning for the WSE results.

The most important discoveries from this work are as follows:

1. For small catchment areas, increasing the size of the cistern had very little or no effect on the WSE, meaning the smallest cistern was the most appropriate.
2. The RWH system can be decommissioned during the months of December through March, and have only a negligible effect on the overall benefit.
3. The set-up cost of the RWH system was only \$0.67 - \$1.50 per $m^3$ of water saved assuming a 20-year life cycle.
4. If the overflow from the system was diverted and used for GWR and the family could later access this water for indoor use, the WSE for each city from RWH alone could be raised by 0.8% for Bangalore, Delhi and Hyderabad, by 2.0% for Kolkata and by 4.4% for Mumbai.
5. The montane climatic region, Srinagar, experienced only a negligible benefit from implementing RWH.

The WSE values varied from 2% to 6% for the smallest catchment area and cistern and from 20% to 50% for the largest catchment area and cistern. Some very interesting trends on the WSE were also discovered:

1. The WSE value always increased with increasing catchment area and cistern volumes. The higher the volume of available water and the larger the storage for long term water retrieval, the more often the daily water demand could be met.
2. An area having a low dry-to-wet ratio can still have a moderate WSE if the total volume of precipitation is high, a result of very high WSE values during the wet months, to raise the overall average from the very poor dry months.

3. An area having a high dry-to-wet ratio can perform poorly on the WSE if the annual precipitation is low.

The most appropriately sized cisterns were calculated and presented for each city and catchment area. The cisterns volume ranged from 757 L to 9464 L, depending on the catchment area, for all the analyzed citied except Mumbai and Srinagar. Mumbai's most appropriate volumes are larger as a result of larger volumes of precipitation and range from 757 L to 18927 L. Srinagar's did not have enough benefit to warrant implementing RWH, as a result of very low precipitation.

## Suggestions for Further Research

Given the immediate and impending water crisis in India of both water quantity and quality, further research in RWH potential for providing water to households is essential. Further areas of research may include:

1. Conduct an analysis of varying demands by varying geographic locations. This study used a constant demand value for every city, while in reality each region of the country likely has a slightly different demand.
2. Conduct a cost to benefit calculation on RWH systems, including cost of material, install and life long maintenance. Can the family perform all maintenance, or will a professional be needed. Given the cost, is there a benefit of the harvester?
3. Analyze the potential benefits of having a groundwater recharge system that diverts the overflow water to recharge the aquifer. A cost to benefit analysis would again be useful.
4. Create a universal demand to supply ratio that could be used in all areas of the country. This ratio should be generic enough so every location that has access to

precipitation data would be able to use the simple formula to assess if a RWH system would benefit them. This will provide a much needed fine resolution tool that can be used by homeowners and policy makers alike.

# APPENDIX A

# WATER USE SURVEY

Table 17: Water use survey conducted by residents of Vishakaputnam, India

| Type of Water Use | Average Volume of Water Consumed for Each Use (estimate in liters) | Please Make a Tick Mark for Each Time Used (water consumed) Each Day | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
| Toilet Flushing | | | | | | | | |
| Hand Washing | | | | | | | | |
| Bathing | | | | | | | | |
| Any other personal maintenance, grooming | | | | | | | | |
| Food Perperation | | | | | | | | |
| Drinking | | | | | | | | |
| Dish Washing | | | | | | | | |
| Clothes Washing | | | | | | | | |
| Other Cleaning | | | | | | | | |
| Oudoor Use (watering of plants, etc) | | | | | | | | |

# APPENDIX B

# PRECIPITATION PATTERNS FOR SIX CITIES OF ANALYSIS

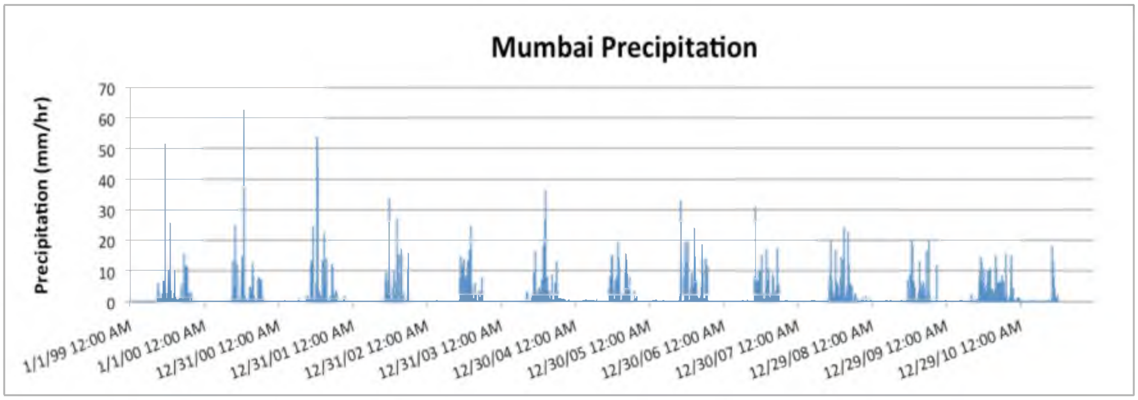


Figure 18: Mumbai precipitation frequency patterns over period of analysis

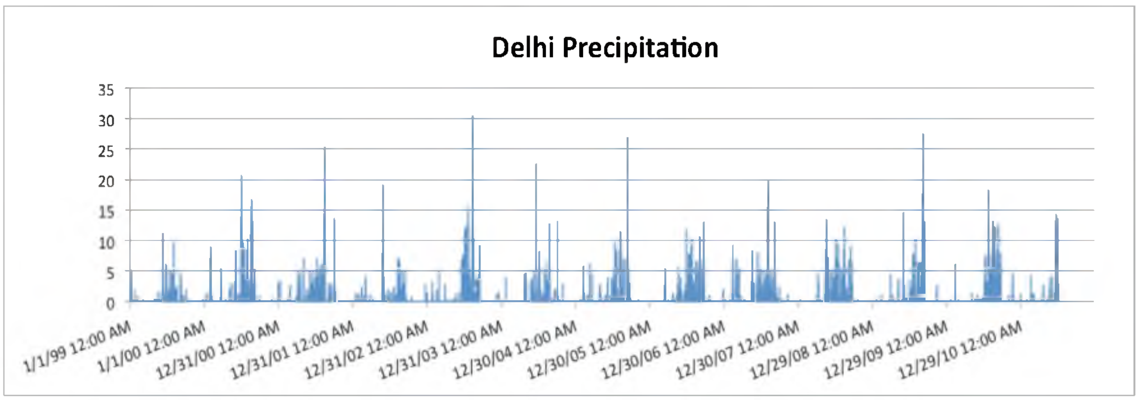


Figure 19: Delhi precipitation patterns over period of analysis

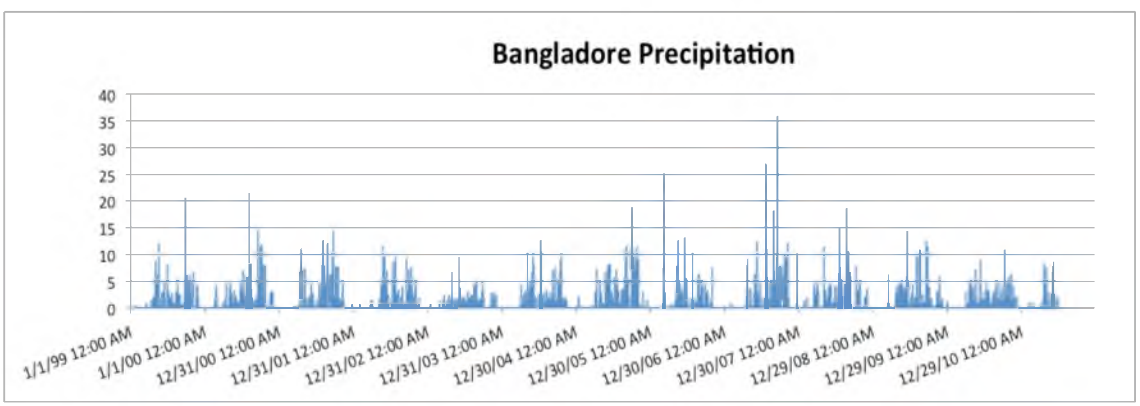


Figure 20: Bangalore precipitation patterns over period of analysis

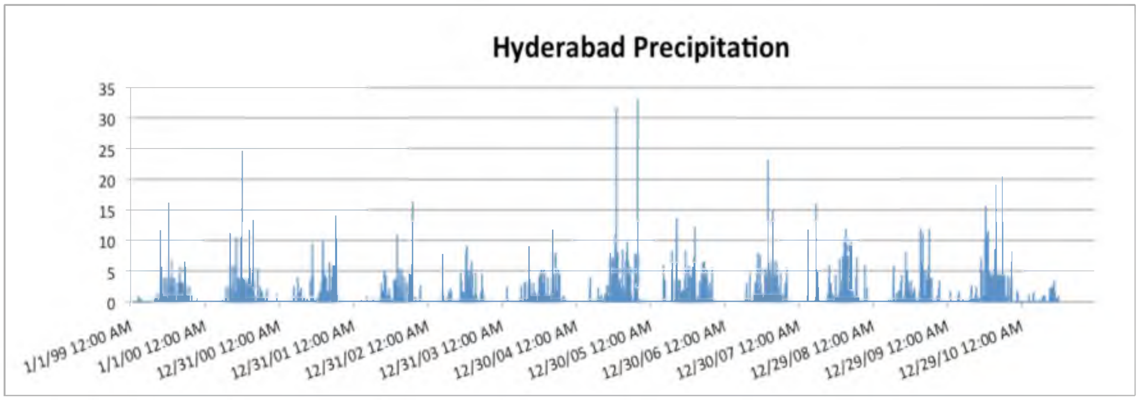


Figure 21: Hyderabad precipitation patterns over period of analysis

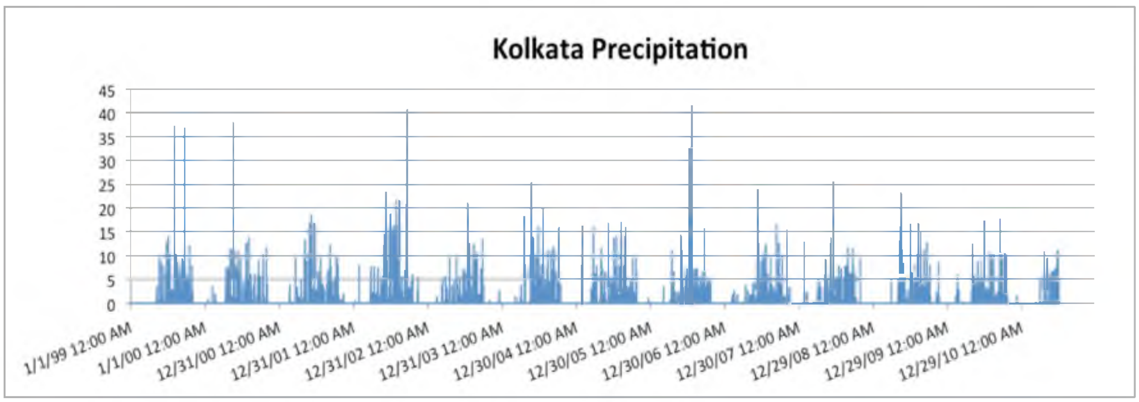


Figure 22: Kolkata precipitation patterns over period of analysis

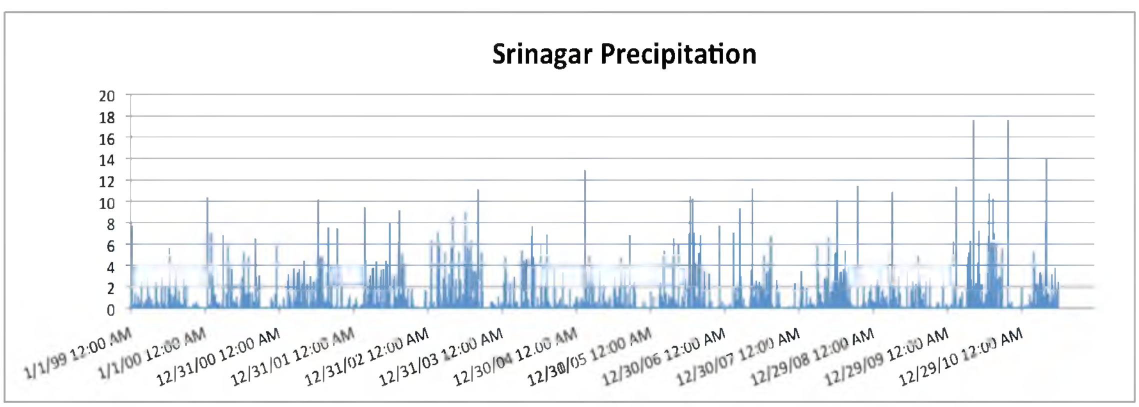


Figure 23: Srinagar precipitation patterns over period of analysis

# APPENDIX C

## PRECIPITATION PATTERNS FOR FOUR ADJACENT QUADRANTS TO MUMBAI CENTROID DURING YEAR 1999

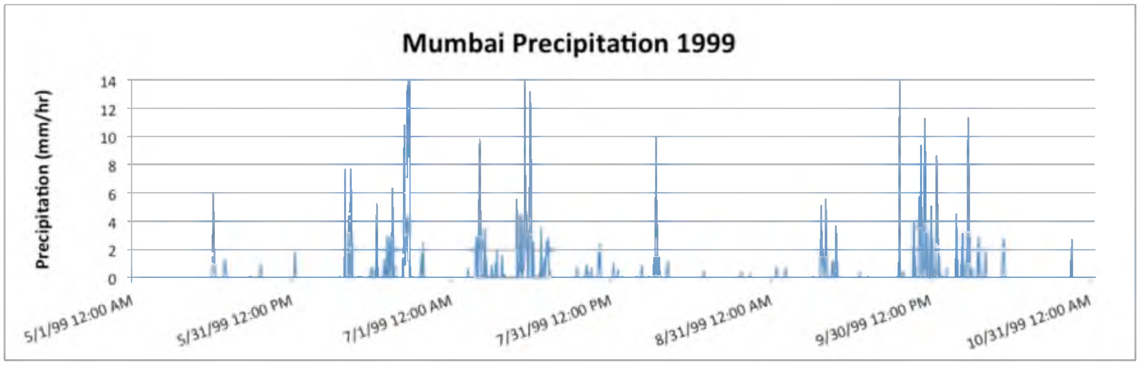


Figure 24: Mumbai centroid precipitation during 1999, periods of no rainfall excluded

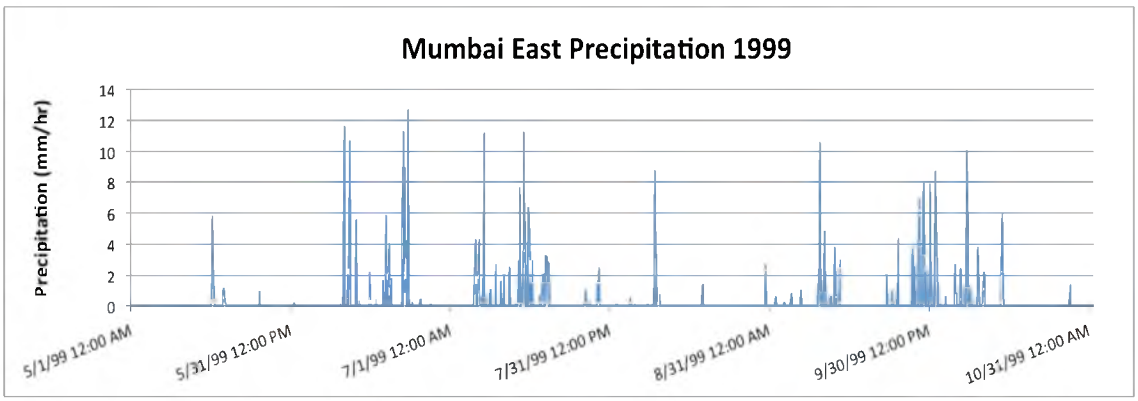


Figure 25: Mumbai east of center precipitation during 1999, periods of no rainfall excluded

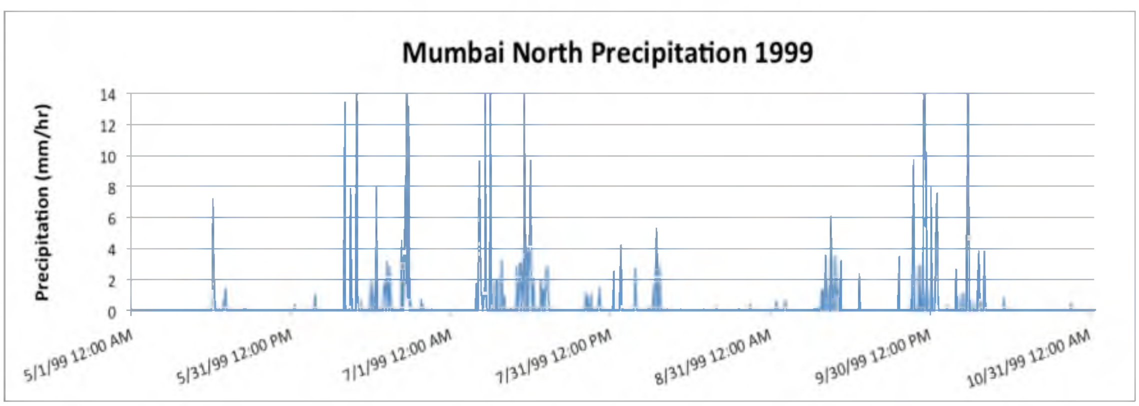


Figure 26: Mumbai north of center precipitation during 1999, periods of no rainfall excluded

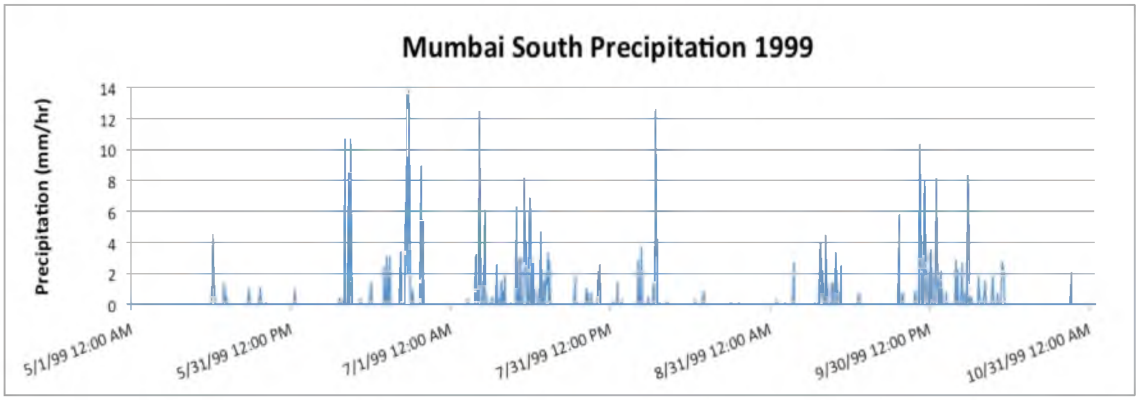


Figure 27: Mumbai south of center precipitation during 1999, periods of no rainfall excluded

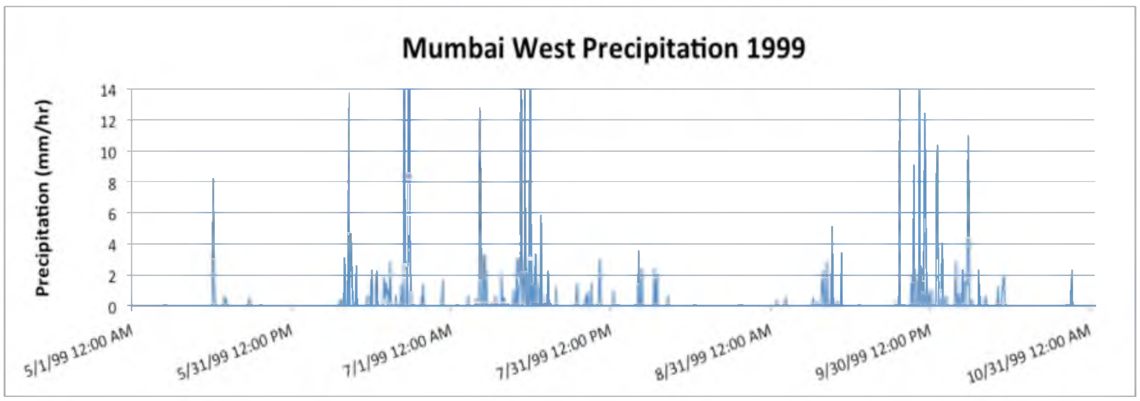


Figure 28: Mumbai west of center precipitation during 1999, periods of no rainfall excluded

# APPENDIX D

# WATER AVAILABLE FOR STORAGE FOR EACH CITY

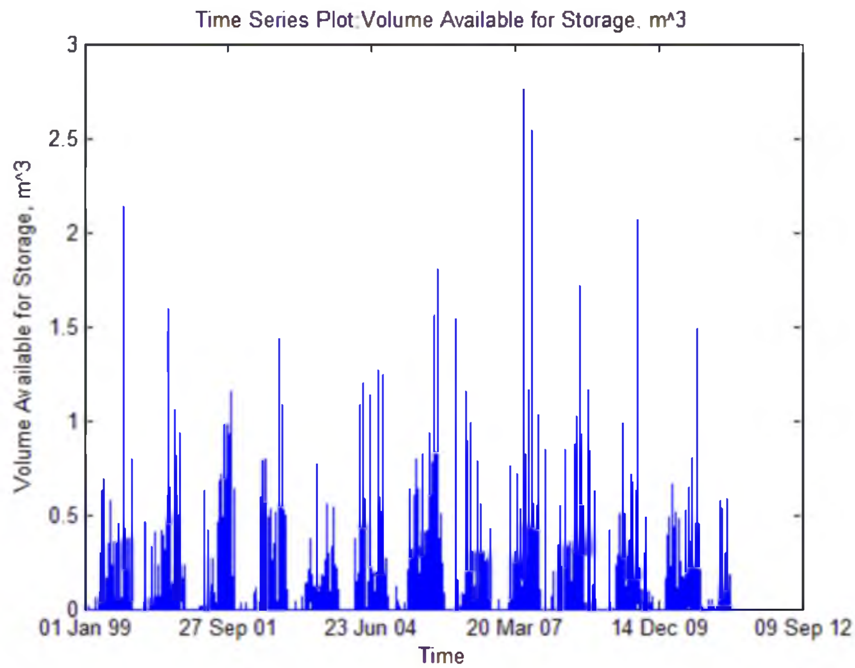


Figure 29: Bangalore volume available for storage

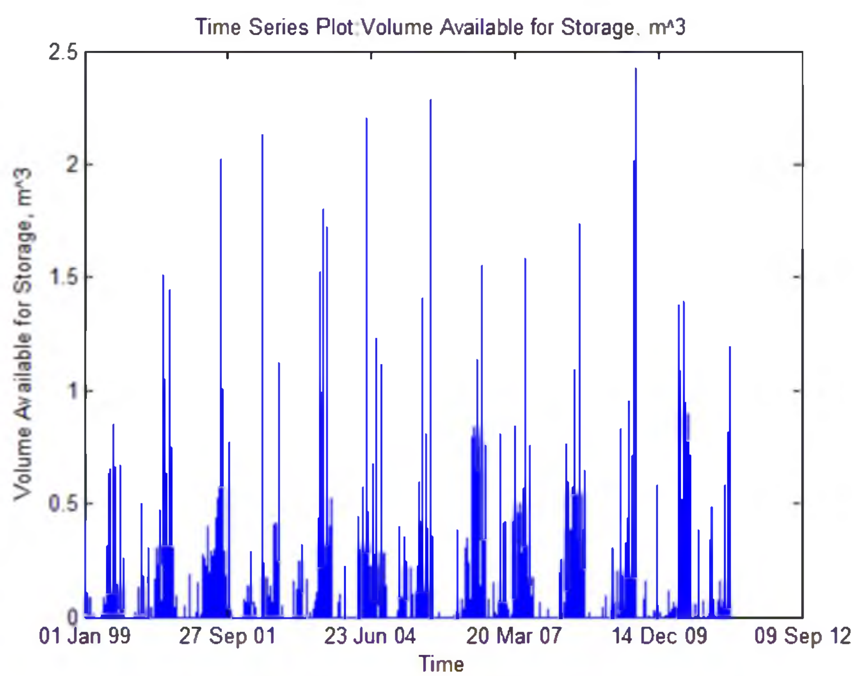


Figure 30: Delhi volume available for storage

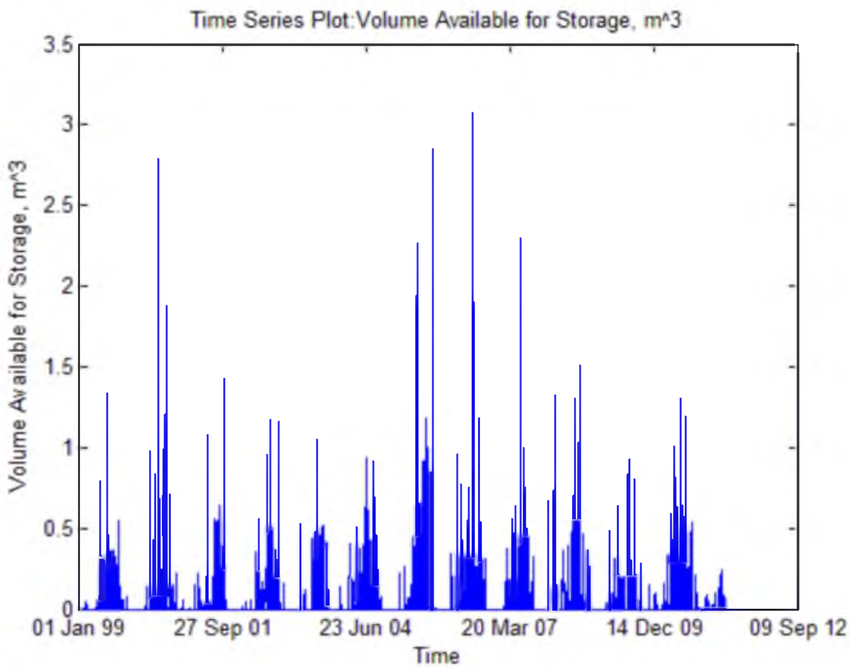


Figure 31: Hyderabad volume available for storage

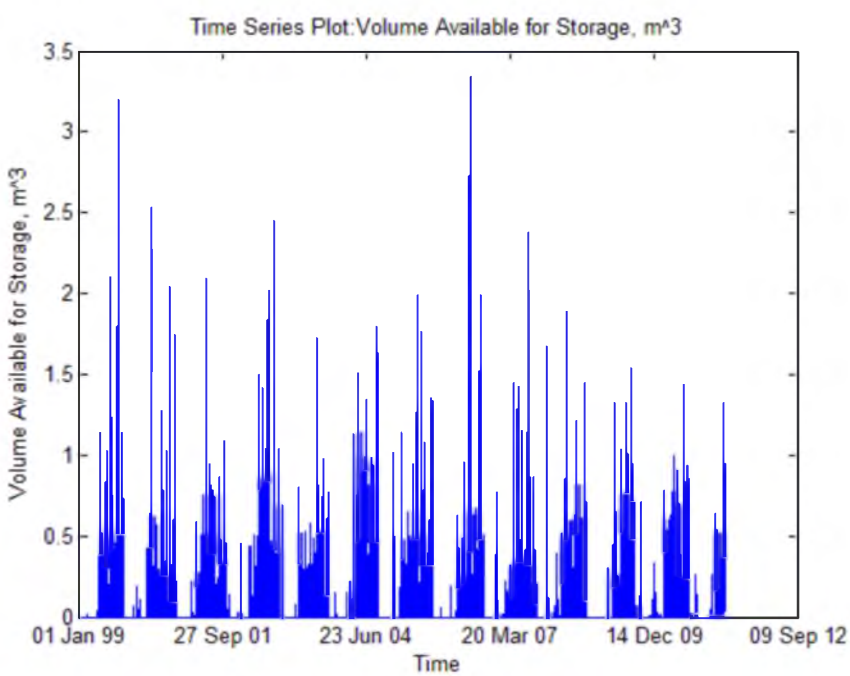


Figure 32: Kolkata volume available for storage

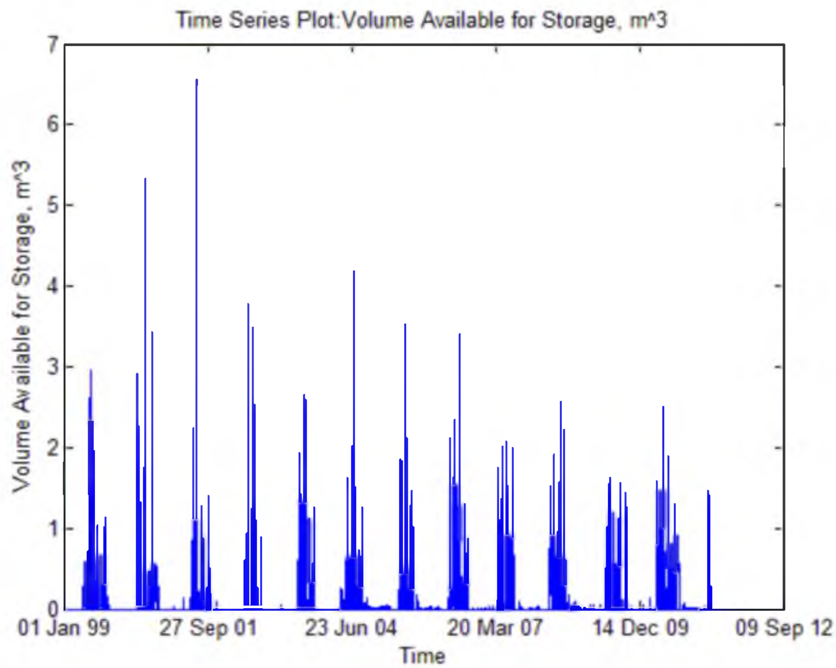


Figure 33: Mumbai volume available for storage

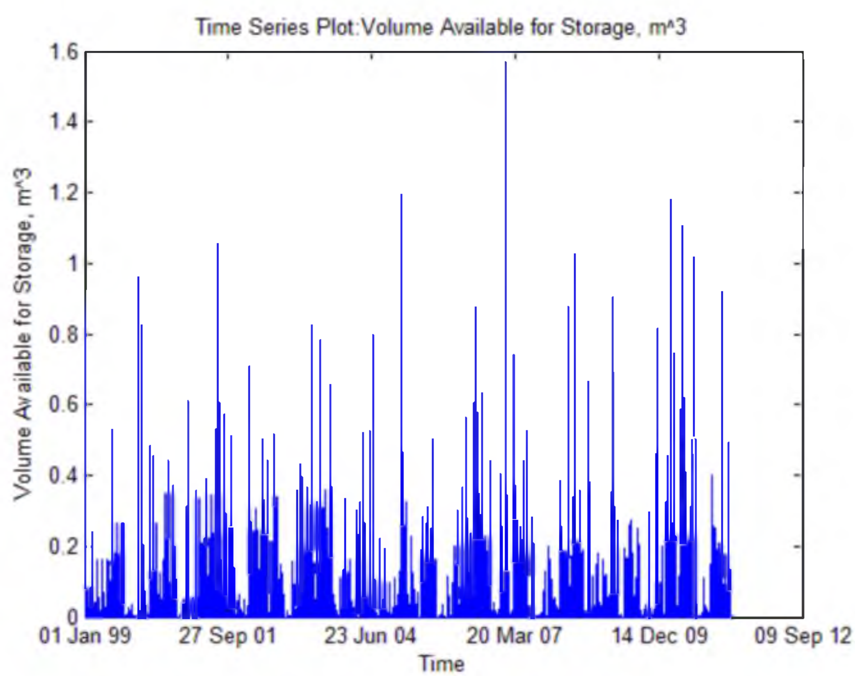


Figure 34: Srinagar volume available for storage

# APPENDIX E

## NUMBER OF DAYS WATER AVAILABLE FOR HOUSEHOLD CONSUMPTION TABLE

Table 18: Number of days water available for household consumption for each cistern size and each method analyzed

| City | Category | Cistern Size (gal) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 200 | 500 | 1000 | 1500 | 2500 | 5000 |
| Bangalore | YBS All | 100 | 109 | 109 | N/A | N/A | N/A |
| | YBS Any | 1253 | 1253 | 1253 | N/A | N/A | N/A |
| | YAS All | 82 | 105 | 109 | N/A | N/A | N/A |
| | YAS Any | 1246 | 1253 | 1253 | N/A | N/A | N/A |
| Delhi | YBS All | 80 | 91 | 92 | N/A | N/A | N/A |
| | YBS Any | 788 | 795 | 796 | N/A | N/A | N/A |
| | YAS All | 58 | 84 | 92 | N/A | N/A | N/A |
| | YAS Any | 777 | 790 | 796 | N/A | N/A | N/A |
| Hyderabad | YBS All | 79 | 87 | 89 | N/A | N/A | N/A |
| | YBS Any | 1079 | 1083 | 1084 | N/A | N/A | N/A |
| | YAS All | 61 | 81 | 89 | N/A | N/A | N/A |
| | YAS Any | 1068 | 1080 | 1084 | N/A | N/A | N/A |
| Kolkata | YBS All | 204 | 223 | 232 | 232 | N/A | N/A |
| | YBS Any | 1277 | 1287 | 1293 | 1293 | N/A | N/A |
| | YAS All | 156 | 210 | 231 | 232 | N/A | N/A |
| | YAS Any | 1257 | 1280 | 1292 | 1293 | N/A | N/A |
| Mumbai | YBS All | 284 | 350 | 387 | 403 | 415 | 417 |
| | YBS Any | 1262 | 1295 | 1316 | 1326 | 1334 | 1336 |
| | YAS All | 197 | 313 | 376 | 398 | 414 | 417 |
| | YAS Any | 1231 | 1275 | 1309 | 1323 | 1334 | 1336 |
| Srinagar | YBS All | 25 | 25 | N/A | N/A | N/A | N/A |
| | YBS Any | 1969 | 1969 | N/A | N/A | N/A | N/A |
| | YAS All | 22 | 25 | N/A | N/A | N/A | N/A |
| | YAS Any | 1968 | 1969 | N/A | N/A | N/A | N/A |

YAS All = Number of days entire demand of water provided for YAS
YAS Any = Number of days any demand of water provided for YAS
YBS All = Number of days entire demand of water provided for YBS
YBS Any = Number of days any demand of water provided for YBS

# APPENDIX F

# PERCENT OF DAYS WATER AVAILABLE FOR HOUSEHOLD CONSUMPTION TABLE

Table 19: Percent of days water available for household consumption for each cistern size and each method analyzed

| City | Category | Cistern Size (gal) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 200 | 500 | 1000 | 1500 | 2500 | 5000 |
| Bangalore | YBS All | **2.2%** | 2.4% | 2.4% | N/A | N/A | N/A |
| | YBS Any | **27.5%** | 27.5% | 27.5% | N/A | N/A | N/A |
| | YAS All | **1.8%** | 2.3% | 2.4% | N/A | N/A | N/A |
| | YAS Any | **27.3%** | 27.5% | 27.5% | N/A | N/A | N/A |
| Delhi | YBS All | **1.8%** | 2.0% | 2.0% | N/A | N/A | N/A |
| | YBS Any | **17.3%** | 17.4% | 17.4% | N/A | N/A | N/A |
| | YAS All | **1.3%** | 1.8% | 2.0% | N/A | N/A | N/A |
| | YAS Any | **17.0%** | 17.3% | 17.4% | N/A | N/A | N/A |
| Hyderabad | YBS All | **1.7%** | 1.9% | 2.0% | N/A | N/A | N/A |
| | YBS Any | **23.6%** | 23.7% | 23.8% | N/A | N/A | N/A |
| | YAS All | **1.3%** | 1.8% | 2.0% | N/A | N/A | N/A |
| | YAS Any | **23.4%** | 23.7% | 23.8% | N/A | N/A | N/A |
| Kolkata | YBS All | **4.5%** | 4.9% | 5.1% | 5.1% | N/A | N/A |
| | YBS Any | **28.0%** | 28.2% | 28.3% | 28.3% | N/A | N/A |
| | YAS All | **3.4%** | 4.6% | 5.1% | 5.1% | N/A | N/A |
| | YAS Any | **27.5%** | 28.0% | 28.3% | 28.3% | N/A | N/A |
| Mumbai | YBS All | 6.2% | **7.7%** | 8.5% | 8.8% | 9.1% | 9.1% |
| | YBS Any | 27.7% | **28.4%** | 28.8% | 29.1% | 29.2% | 29.3% |
| | YAS All | 4.3% | **6.9%** | 8.2% | 8.7% | 9.1% | 9.1% |
| | YAS Any | 27.0% | **27.9%** | 28.7% | 29.0% | 29.2% | 29.3% |
| Srinagar | YBS All | **0.5%** | 0.5% | N/A | N/A | N/A | N/A |
| | YBS Any | **43.1%** | 43.1% | N/A | N/A | N/A | N/A |
| | YAS All | **0.5%** | 0.5% | N/A | N/A | N/A | N/A |
| | YAS Any | **43.1%** | 43.1% | N/A | N/A | N/A | N/A |

YAS All = Number of days entire demand of water provided for YAS
YAS Any = Number of days any demand of water provided for YAS
YBS All = Number of days entire demand of water provided for YBS
YBS Any = Number of days any demand of water provided for YBS

# APPENDIX G

## VOLUME WATER STORED IN HARVESTER CISTERN AFTER DAILY DEMAND REMOVED (200 GALLON CISTERN)

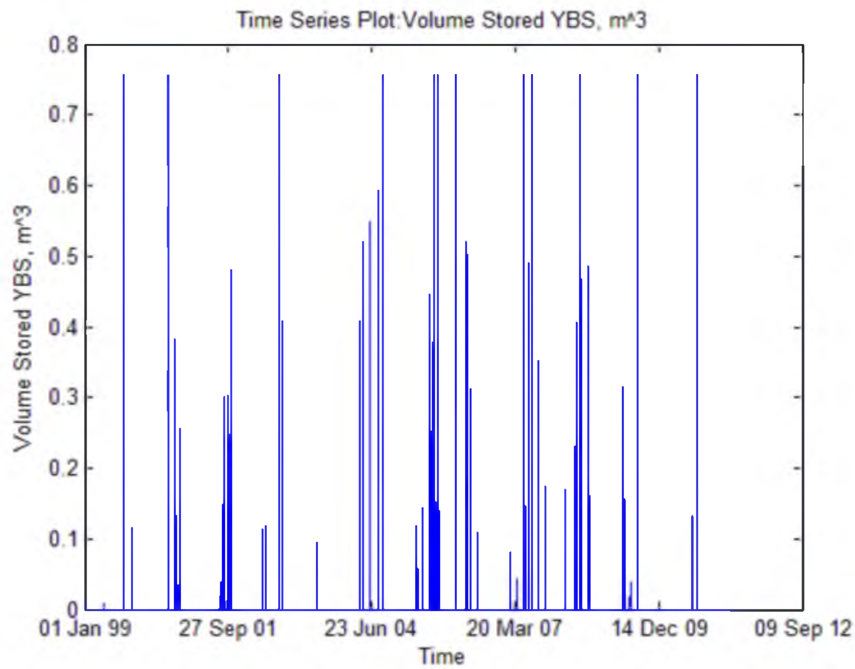


Figure 35: Bangalore volume storage in cistern, YBS algorithm

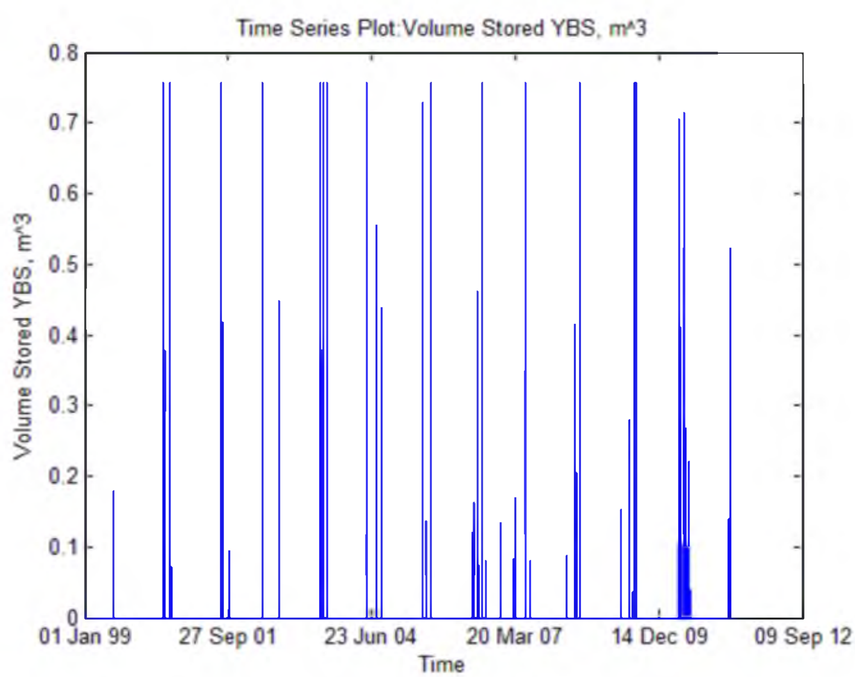


Figure 36: Delhi volume storage in cistern, YBS algorithm

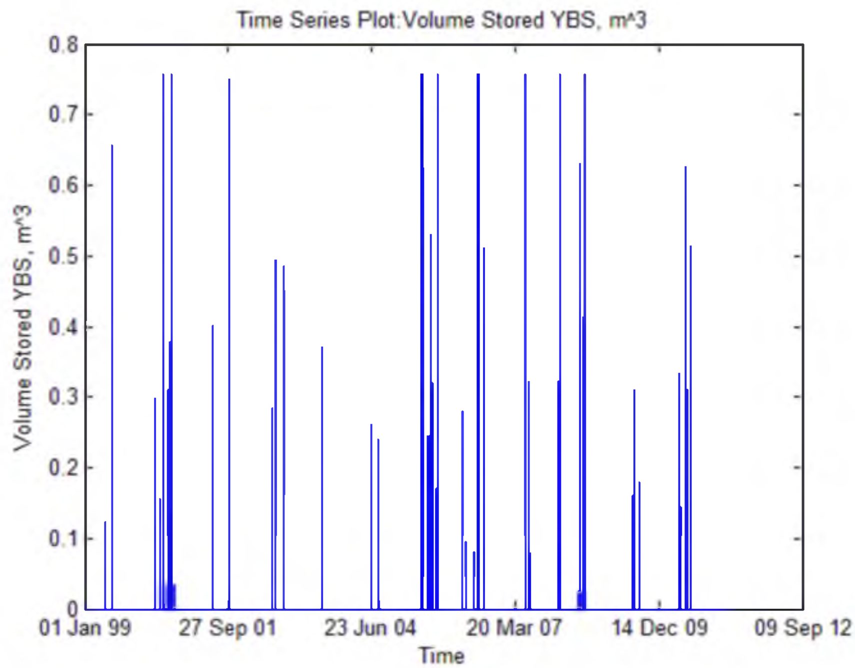


Figure 37: Hyderabad volume storage in cistern, YBS algorithm

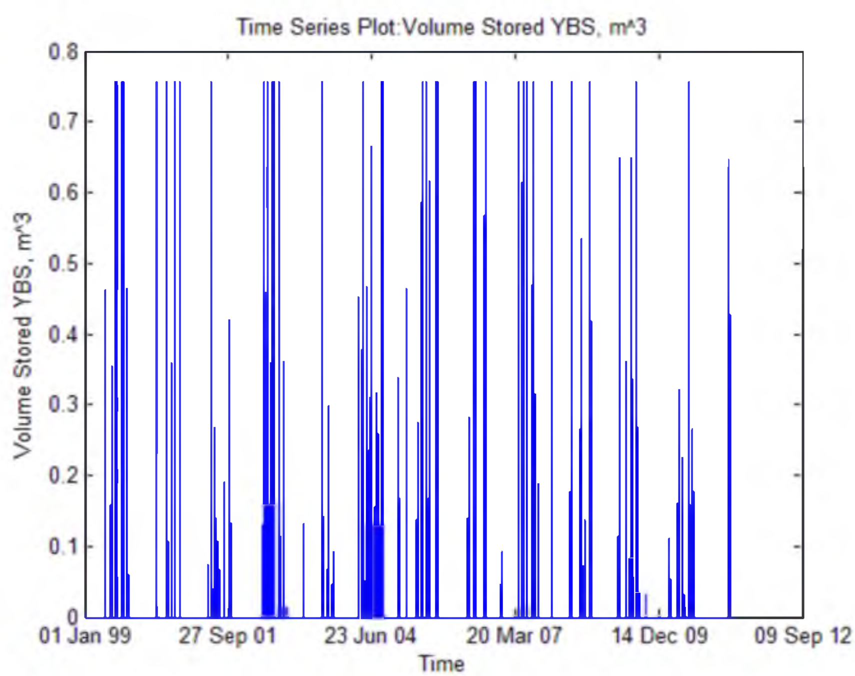


Figure 38: Kolkata volume storage in cistern, YBS algorithm

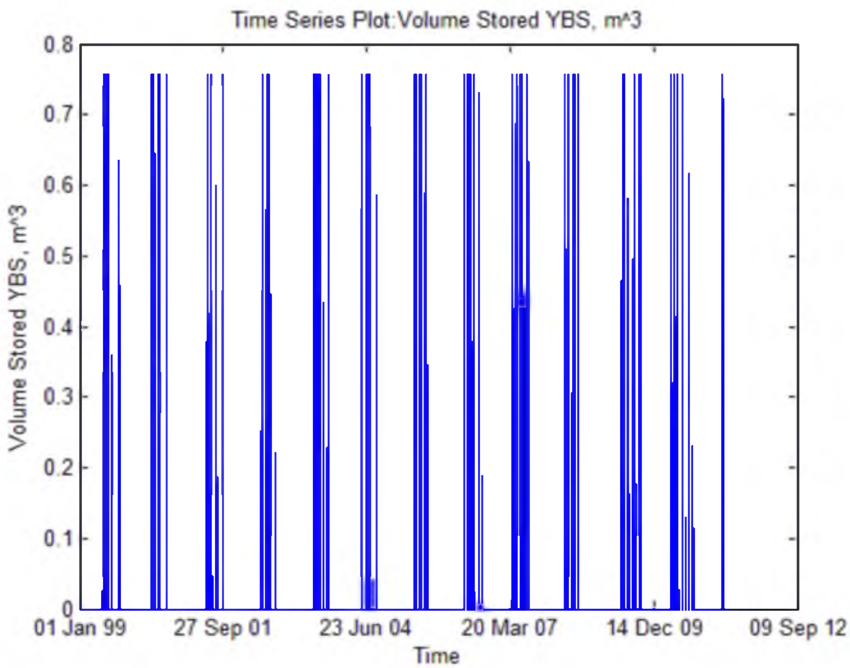


Figure 39: Mumbai volume storage in cistern, YBS algorithm

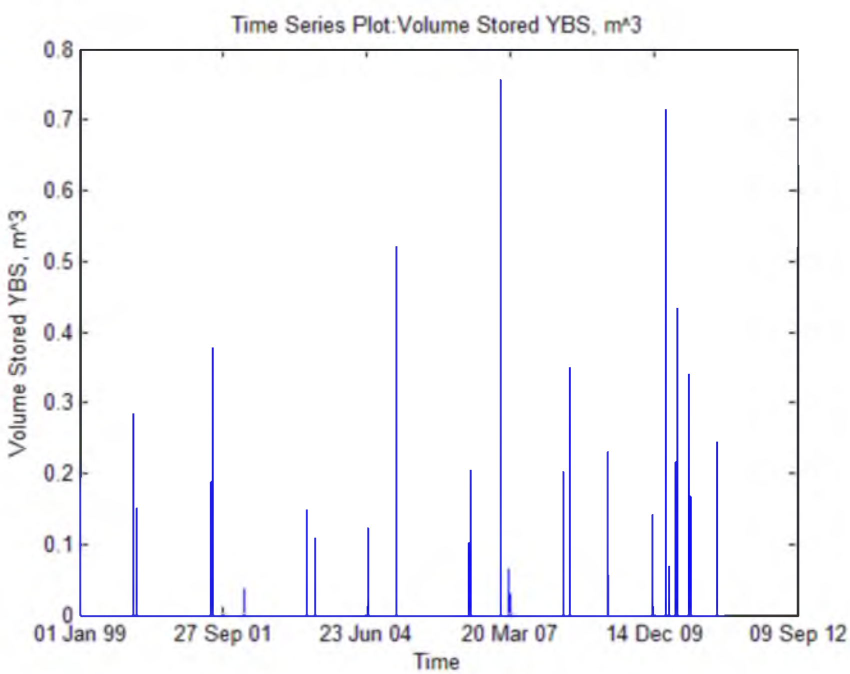


Figure 40: Srinagar volume storage in cistern, YBS algorithm

# APPENDIX H

## VOLUME OF WATER LOST FROM HARVESTER CISTERN

## AS A RESULT OF OVERFLOW (200 GALLON CISTERN)

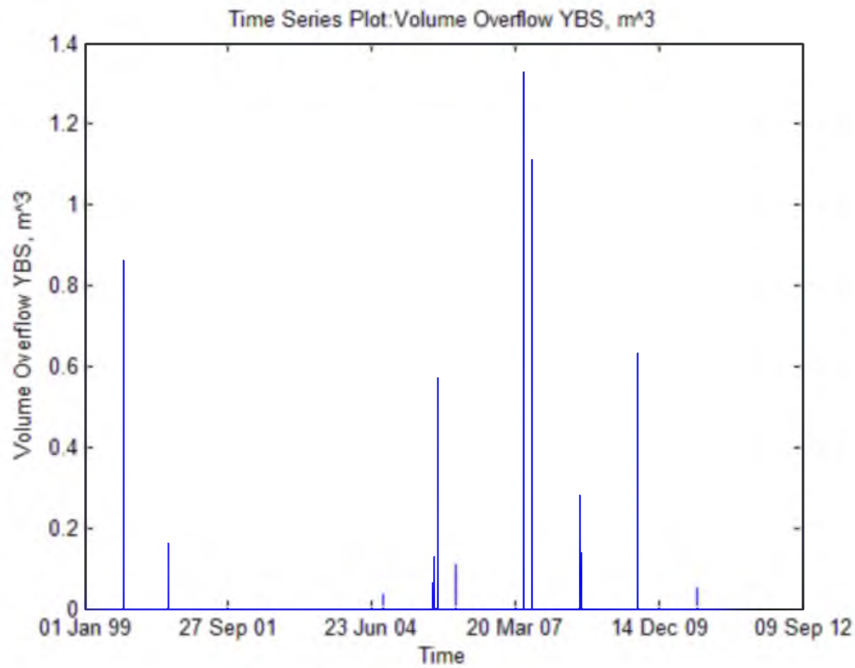


Figure 41: Bangalore volume overflow from cistern, YBS algorithm

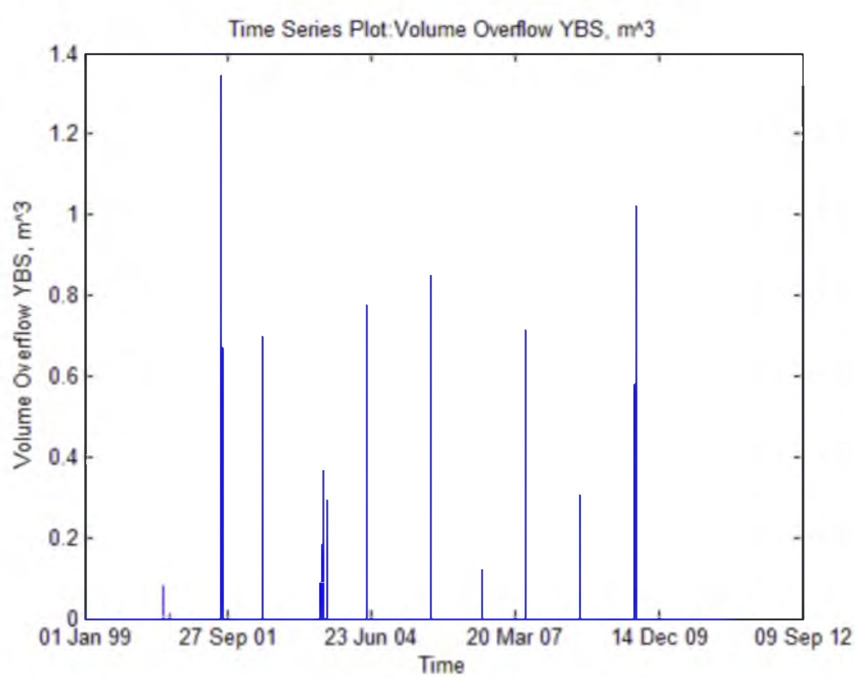


Figure 42: Delhi volume overflow from cistern, YBS algorithm

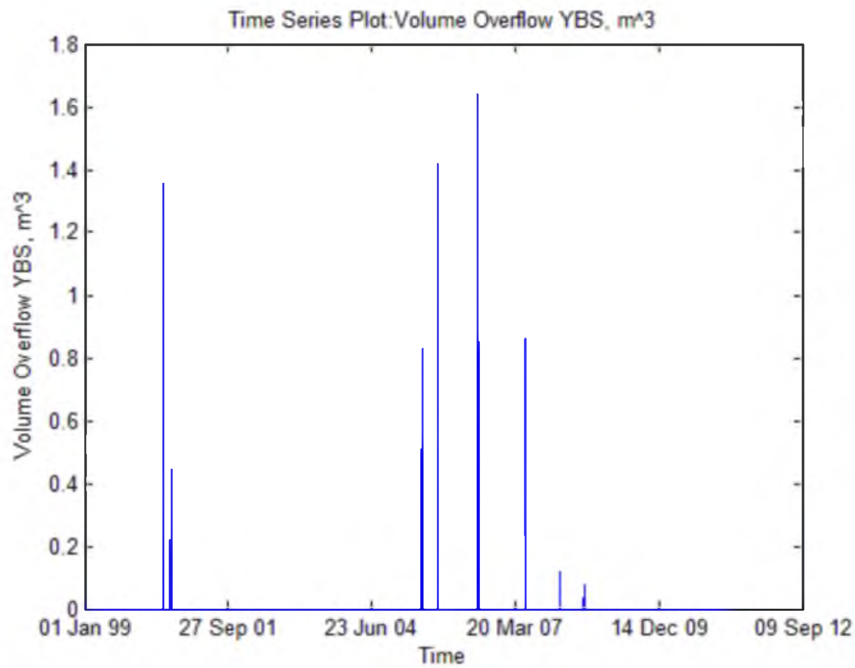


Figure 43: Hyderabad volume overflow from cistern, YBS algorithm

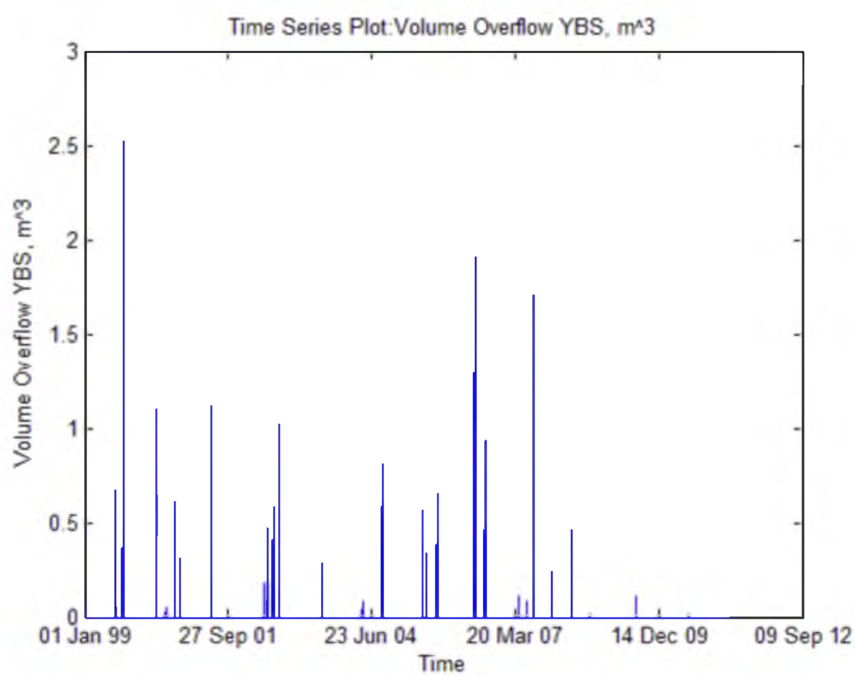


Figure 44: Kolkata volume overflow from cistern, YBS algorithm

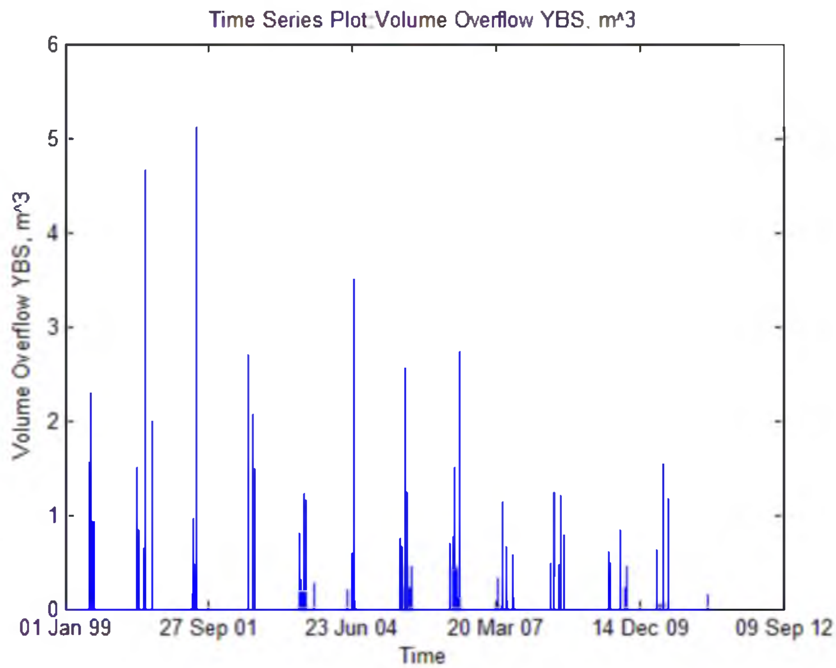


Figure 45: Mumbai volume overflow from cistern, YBS algorithm

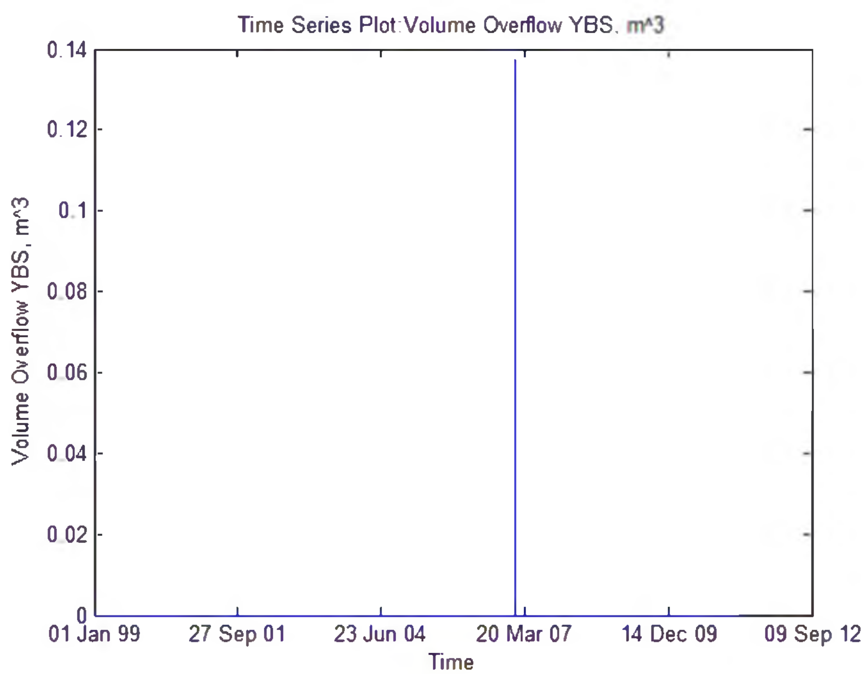


Figure 46: Srinagar volume overflow from cistern, YBS algorithm

# APPENDIX I

# MATLAB CODE

Extract of code from dataExtract.m

This code was the first of two programs used to extract the TRMM precipitation data from the NETcfd files. 36000 files were downloaded from NASA servers, each containing a grid of precip frequency data for that three-hour increment. Each file had a different name, this code was written strictly for creating a string of the filename, which was used by the openNsave.m program to open the file and extract the data.

```
%  Program created 13 Nov 2012 by Dan Stout, MS Civil Engineering
%  Attempts to extract all of the rainfall intensity values from a
%  large number of TRMM files for one location (grid cell).  The user %
will need to input which cell is needed.

clear
% create global var that can be called in "openNsave"
global y; global m; global d; global h; global n; global countneg;
global countmiss; global a;
precipIntensities = zeros(248,5); % for openNsave program to store data
% create a loop the will create file names in order to be opened
% set initial values
y = 99; m = 1; d = 1; h = 0; n = 0; countneg = 0; countmiss = 0; a = 1;

global filename

% seperate loop for Y 1999
for y = 99
  % jan 1999
  for m = 1
    for d = 1:31
      for h = 0:3:21
        filename = sprintf('nc_3B42.%i%02i%02i.%i.6.HDF.Z.nc',y,m,d,h)
        cd('/Users/stout/Dropbox/thesis work (shared with
steve)/_assets/MATLAB code/DansCode/');
        run('openNsave')
      end
    end
  end
  % write data to an external spreadsheet each month
  xlswrite('saveData0199.xlsx',precipIntensities,1,sprintf('A%i',a))
  % clear precipIntensities var so longer month values not be in
shorter
  clearvars precipIntensities
  % a is a place keeper to tell where to write in excel see "openNsave"
  a = a + n;
  % n is a place holder  for creating each month matrix see "openNsave"
  n = 0;
```

This same process was run for each month from Jan 1999 to Jun 2011.

Extract of code from openNsave.m

Once dataExtract.m created the filename it called this script. This script opens the NetCDF file using MATLAB commands specifically for this type of file, then saves the needed data in the precipIntensities matrix. The "`value = intensity(58,39);`" line is where the user must input the grid cell of interest.

```
%  Program created 18 Nov 2012, by Dan Stout, MS CVEEN, University of
%  Utah.  This script is a sub-script of "dataExtract.m"

global filename
global y; global m; global d; global h; global n; global countneg;
global countmiss; global a;

cd('D:\Dropbox\Thesis Work (shared with Steve)\_assets\Rain
Data\NASA_TRMM,3hr\actual data (1jan99-30jun11)');

% Open the file and get an ID for the file
% (http://www.mathworks.com/help/matlab/ref/NetCDF.open.html)
ncid = NetCDF.open(filename,'NOWRITE');

% From testing the file, I know that variable 1 contains the
% precipitation values. Thus need to write var 1 to a matrix, then can
% extract the cell desired.

% get info about first variable
% (http://www.mathworks.com/help/matlab/ref/NetCDF.inqvar.html)
[varname1, xtype1, dimids1, numatts1] = NetCDF.inqVar(ncid,0);
% get variable ID of the first variable, given its name
% (http://www.mathworks.com/help/matlab/ref/NetCDF.inqvarid.html)
varid1 = NetCDF.inqVarID(ncid,varname1);
% get the data from the first varaible given its varid
% (http://www.mathworks.com/help/matlab/ref/NetCDF.getvar.html)
intensity = NetCDF.getVar(ncid,varid1);

% ****** now extract desired cell ****
% note that its the inverse of the Excel cell, thus if the cell is
% (A,B) in EXCEL, it needs to be (B,A) here
value = intensity(58,39);
% clear intensity variable to conserve memory
clearvars intensity

% n is used to keep track of where the values need to be stored in the
% matrix, will be reset after each month
% a is used to know what line the data should be exported in excel,
% and should never be reset
n = n+1;
precipIntensities(n,1) = y;
precipIntensities(n,2) = m;
precipIntensities(n,3) = d;
precipIntensities(n,4) = h;
precipIntensities(n,5) = value;
```

The script terminated and returns to dataExtract to continue running.

Extract of code from RWHanalyzer.m (5 pages)
This script performs the mass balance calculations for both YBS and YAS, creates plots, and preforms the monthly water saving efficiency calculations.

```
%  Program to perform mass balance calculation for Rain water harvesing
%  analysis for thesis research.
%  Dan Stout, University of Utah
%  Started 16 July 2013
%  14 Aug 13 added Water Saving Efficiency (WSE) per month

% This script will create several tabs in the input file Excel
% Spreadsheet.
% Sheet one is assumed to be the TRMM precip data (input data).


%%%%% NOTE:  Each time the program is run, the following needs to be
%%%%% input/changed: tnkvol_gal (line 23), filename (line 37),
%%%%% city (line 39).  DO NOT CHANGE ANYTHING ELSE!!!!

clear; i=0; wtr_in_matrix = zeros(36512,1); wtr_in_matrix_day =
zeros(4564,1);
V_YBS = zeros(4564,1); V_YBS_spill = zeros(4564,1); V_YBS_store =
zeros(4564,1);
V_YAS = zeros(4564,1); V_YAS_spill = zeros(4564,1); V_YAS_store =
zeros(4564,1);
V_YBS_full = zeros(4564,1); V_YBS_any = zeros(4564,1);
V_YAS_full = zeros(4564,1); V_YAS_any = zeros(4564,1);

% input cistern volume in (cubic meters)(1000 L = 1 m^3) (264.2 gal = 1
m^3)
tnkvol_gal = 500; % 200, 500, 1000, 1500, 2500, 5000
tnkvol = tnkvol_gal/264.2;
% input daily water use in (cubic meters)
wtr_use = 675/1000;
% input Runoff Coeff
RC = 0.9;
% input roof (catchment) area in (square meters)
area = 21;

% Use the collection volume equation to calculate the volume of water
% entering the cistern with a given volume of rainfall.  ** Note the
% rainfall data is an average intensity over three hours with units of
% mm/hr.  Thus to get the volume of water, each value needs to be
% multiplied by 3 hours (units of mm).
% A conversion factor must be used to convert m^2*mm to m^3.
filename = 'Bangalore_main_QCdone_oct03nov06add.xlsx';  % input file
city = 01;  % input city code for graphics printing; 01 = Bangalore, 02
= Delhi, 03 = Hyderabad, 04 = Kolkata, 05 = Mumbai, 06 = Srinagar
raindata = xlsread(filename);  % read in the precip data
for i = 1:36512
  wtr_in = raindata(i,5)*3*RC*area*(1/1000); % volume equation
  wtr_in_matrix(i,1) = wtr_in;
end
% write all water_in_matrix (inflow into cistern) into Sheet2 of the
input
% file.
```

```
xlswrite(filename,tnkvol_gal,'tnkvol_gal');
xlswrite(filename,wtr_in_matrix,'water_in_m3_3hr');

% Combine 3 hour wtr_in to daily values
% note wtr_in_matrix_day(1,1) is water in for 01jan99.  Each line is
% one day later
n=0;
for i = 1:4564 % 36512/8 = 4564
  n=n+1; tmp_for_sum(1,1) = wtr_in_matrix(n,1);
  n=n+1; tmp_for_sum(2,1) = wtr_in_matrix(n,1);
  n=n+1; tmp_for_sum(3,1) = wtr_in_matrix(n,1);
  n=n+1; tmp_for_sum(4,1) = wtr_in_matrix(n,1);
  n=n+1; tmp_for_sum(5,1) = wtr_in_matrix(n,1);
  n=n+1; tmp_for_sum(6,1) = wtr_in_matrix(n,1);
  n=n+1; tmp_for_sum(7,1) = wtr_in_matrix(n,1);
  n=n+1; tmp_for_sum(8,1) = wtr_in_matrix(n,1);
  A = sum(tmp_for_sum);
  wtr_in_matrix_day(i,1) = A;
  %wtr_in_matrix_day(i,2) =
end
xlswrite(filename,wtr_in_matrix_day,'water_in_m3_day');


% YIELD BEFORE SPILLAGE
% Calculate the volume of water available for storage
% V(available) = V(stored from previous time) + wtr_in - wtr_use
V_YBS(1,1) = 0 + wtr_in_matrix_day(1,1) - wtr_use; % assume cistern
start empty
V_YBS_full(1,1) = 0; % see notes in for statement below for definition
of this variable.  Assume =0 at day 1.
V_YBS_any(1,1) = 0; % same note as previous line
if V_YBS(1,1) < 0
  V_YBS(1,1) = 0;
end
% Calculate the spillage and the actual volume stored
if V_YBS(1,1) > tnkvol
  V_YBS_spill(1,1) = V_YBS(1,1) - tnkvol;
  V_YBS_store(1,1) = tnkvol;
else
  V_YBS_spill(1,1) = 0;
  V_YBS_store(1,1) = V_YBS(1,1);
end
for i = 2:4564
  V_YBS(i,1) = V_YBS_store(i-1,1) + wtr_in_matrix_day(i,1) - wtr_use;
  % assign a value of 1 if the family was able to get ALL indoor water
use
  % that day from RWH
  if V_YBS(i,1) > 0
    V_YBS_full(i,1) = 1;
  else
    V_YBS_full(i,1) = 0;
  end
  % assign a value of 1 if the family was able to get ANY indoor water
use
  % that day from RWH
  if V_YBS_store(i-1,1) + wtr_in_matrix_day(i,1) > 0
    V_YBS_any(i,1) = 1;
  else
```

```
    V_YBS_any(1,1) = 0;
  end
  %get rid of neg volumes, unrealistic
  if V_YBS(i,1) < 0
  V_YBS(i,1) = 0;
  end
  % Calculate the spillage and the actual volume stored
  if V_YBS(i,1) > tnkvol
  V_YBS_spill(i,1) = V_YBS(i,1) - tnkvol;
  V_YBS_store(i,1) = tnkvol;
  else
  V_YBS_spill(i,1) = 0;
  V_YBS_store(i,1) = V_YBS(i,1);
  end
end
xlswrite(filename,V_YBS_spill,'vol_YBS_m3_overflow');
xlswrite(filename,V_YBS_store,'vol_YBS_m3_stored');

% YIELD AFTER SPILLAGE
V_YAS(1,1) = 0 + wtr_in_matrix_day(1,1); % assume cistern start empty
V_YAS_full(1,1) = 0; % see notes in for statement below for definition
of this variable.  Assume =0 at day 1.
V_YAS_any(1,1) = 0; % same note as previous line
if V_YAS(1,1) > tnkvol
  V_YAS_spill(1,1) = V_YAS(1,1) - tnkvol;
  V_YAS_store(1,1) = tnkvol - wtr_use;
else
  V_YAS_spill(1,1) = 0;
  V_YAS_store(1,1) = V_YAS(1,1) - wtr_use;
end
if V_YAS_store(1,1) < 0
  V_YAS_store(1,1) = 0;
end
for i = 2:4564
  V_YAS(i,1) = V_YAS_store(i-1,1) + wtr_in_matrix_day(i,1);

  if V_YAS(i,1) > tnkvol
    V_YAS_spill(i,1) = V_YAS(i,1) - tnkvol;
    V_YAS_store(i,1) = tnkvol - wtr_use;
  else
    V_YAS_spill(i,1) = 0;
    V_YAS_store(i,1) = V_YAS(i,1) - wtr_use;
  end
  %get rid of neg volumes, unrealistic
  if V_YAS_store(i,1) < 0
    V_YAS_store(i,1) = 0;
  end
  % assign a value of 1 if the family was able to get ALL indoor water
use
  % that day from RWH
  if V_YAS_store(i,1) > 0
    V_YAS_full(i,1) = 1;
  else
    V_YAS_full(i,1) = 0;
  end
  % assign a value of 1 if the family was able to get ANY indoor water
use
  % that day from RWH
```

```
  if V_YAS_store(i-1,1) + wtr_in_matrix_day(i,1) > 0
    V_YAS_any(i,1) = 1;
  else
    V_YAS_any(i,1) = 0;
  end
end

%Compile data and send to Excel
numDaysYBSprovideALL = sum(V_YBS_full);
numDaysYBSprovideANY = sum(V_YBS_any);
numDaysYASprovideALL = sum(V_YAS_full);
numDaysYASprovideANY = sum(V_YAS_any);
xlswrite(filename,V_YAS_spill,'vol_YAS_m3_overflow');
xlswrite(filename,V_YAS_store,'vol_YAS_m3_stored');
xlswrite(filename,numDaysYBSprovideALL,'numDaysYBSprovideALL');
xlswrite(filename,numDaysYBSprovideANY,'numDaysYBSprovideANY');
xlswrite(filename,numDaysYASprovideALL,'numDaysYASprovideALL');
xlswrite(filename,numDaysYASprovideANY,'numDaysYASprovideANY');

%Create 5 plots, V_YBS_store, V_YBS_spill, V_YAS_store, V_YAS_spill,
wtr_in
%
ts = timeseries(V_YBS_store,1:4564);
ts.Name = 'Volume Stored YBS, m^3';
ts.TimeInfo.Units = 'days';
ts.TimeInfo.StartDate = '01-Jan-1999';
ts.TimeInfo.Format = 'dd mmm yy';
ts.Time=ts.Time-ts.Time(1);
h = figure; plot(ts);
filename = sprintf('VolstoreYBS_city%02i_cistern%02i',city,tnkvol_gal);
saveas(h, filename, 'bmp');
%
ts = timeseries(V_YBS_spill,1:4564);
ts.Name = 'Volume Overflow YBS, m^3';
ts.TimeInfo.Units = 'days';
ts.TimeInfo.StartDate = '01-Jan-1999';
ts.TimeInfo.Format = 'dd mmm yy';
ts.Time=ts.Time-ts.Time(1);
h = figure; plot(ts);
filename = sprintf('VolspillYBS_city%02i_cistern%02i',city,tnkvol_gal);
saveas(h, filename, 'bmp');
%
ts = timeseries(V_YAS_store,1:4564);
ts.Name = 'Volume Stored YAS, m^3';
ts.TimeInfo.Units = 'days';
ts.TimeInfo.StartDate = '01-Jan-1999';
ts.TimeInfo.Format = 'dd mmm yy';
ts.Time=ts.Time-ts.Time(1);
h = figure; plot(ts);
filename = sprintf('VolstoreYAS_city%02i_cistern%03i',city,tnkvol_gal);
saveas(h, filename, 'bmp');
%
ts = timeseries(V_YAS_spill,1:4564);
ts.Name = 'Volume Overflow YAS, m^3';
ts.TimeInfo.Units = 'days';
ts.TimeInfo.StartDate = '01-Jan-1999';
ts.TimeInfo.Format = 'dd mmm yy';
ts.Time=ts.Time-ts.Time(1);
```

```
h = figure; plot(ts);
filename = sprintf('VolspillYAS_city%02i_cistern%03i',city,tnkvol_gal);
saveas(h, filename, 'bmp');
%
ts = timeseries(wtr_in_matrix_day,1:4564);
ts.Name = 'Volume Available for Storage, m^3';
ts.TimeInfo.Units = 'days';
ts.TimeInfo.StartDate = '01-Jan-1999';
ts.TimeInfo.Format = 'dd mmm yy';
ts.Time=ts.Time-ts.Time(1);
h = figure; plot(ts);
filename =
sprintf('VolAvailable_city%02i_cistern%03i',city,tnkvol_gal);
saveas(h, filename, 'bmp');


% Water Saving Efficiency Calculations, monthly basis
% Efficiency = SUM(water_in) / SUM(demand) * 100
count = 0; counter = 0; wtr_sav_eff_matrix = zeros(150,3);

for y = 1999
  %jan, 31 days
  m = 1; Demand = wtr_use * 31; counter = counter + 1;
  count = count+1; Yield = wtr_in_matrix_day(count,1);
  for j = 2:31
    count = count+1;
    Yield = Yield + wtr_in_matrix_day(count,1);
  end
  wtr_sav_eff = Yield/Demand *100;
  wtr_sav_eff_matrix(counter,1) = y; wtr_sav_eff_matrix(counter,2) = m;
wtr_sav_eff_matrix(counter,3) = wtr_sav_eff;


......

  %jun, 30 days
  m = 6; Demand = wtr_use * 30; counter = counter + 1;
  count = count+1; Yield = wtr_in_matrix_day(count,1);
  for j = 2:30
    count = count+1;
    Yield = Yield + wtr_in_matrix_day(count,1);
  end
  wtr_sav_eff = Yield/Demand *100;
  wtr_sav_eff_matrix(counter,1) = y; wtr_sav_eff_matrix(counter,2) = m;
wtr_sav_eff_matrix(counter,3) = wtr_sav_eff;

end

xlswrite(filename,wtr_sav_eff_matrix,'wtr_sav_eff_matrix_%');
```

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